33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Toward ‘optimal’ schemes of robot assistance to facilitate motor skill learning

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Abstract— **We investigate whether and on what circumstances physical interaction with a robot may facilitate the acquisition of a novel motor skill. We focus on two different motor tasks: (i) intermanual transfer of cursive handwriting and (ii) acquisition of a putting skill. In the case of handwriting, we found that intermanual transfer is facilitated by forms of interaction that account for the temporal aspects of the movements. In the case of putting, we found that guidance is helpful in improving longitudinal error (a matter of speed accuracy), but not directional error (a matter of position accuracy). Based on these results, we draw some tentative conclusions on which tasks can benefit from guidance, and how robots should be programmed to maximize their effect.**

I. INTRODUCTION

OVER the years, many studies have claimed that physical interaction with a robotic ‘trainer’ may facilitate the acquisition of a novel motor skill. More specifically, skill acquisition may be faster if trainees are allowed to experiment the correct movements, and/or they are prevented from performing incorrect ones (the ‘guidance’ hypothesis); see [1] for a recent review. Alternatively, robots could be used to make the task more challenging, for instance by providing perturbations or resistive forces. In all cases, a comprehensive theory of the mechanisms of action of guidance (or other forms of interaction) is still lacking.

Many questions remain open. Is guidance - or other forms of interaction - effective in promoting the acquisition of at least some categories of motor skills? If so, what are its mechanisms of action? Furthermore, are there ‘optimal’ forms of interaction, which maximize skill acquisition?

A better understanding of how humans acquire novel motor skills (and how robots can be used to facilitate such learning) may pave the way to novel applications of robots and may suggest more principled ways to use robots to promote neuromotor recovery.

To address these issues, here we focus on the use of robots to facilitate the acquisition of two different skills: (i) intermanual transfer of handwriting, i.e. learning how to write with the non-dominant hand, and (ii) ‘putting’ movements, in which an object must be hit in order to be moved into a target region. Based on our results, we draw some tentative conclusions on which tasks can benefit from guidance, and how robots should be programmed to maximize their effect.

This work is partly supported by the EU grant FP7-ICT-231724 HUMOUR.
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II. ROBOTS AND MOTOR SKILL LEARNING

A. Modeling motor skill acquisition

We have a limited knowledge of the computational mechanisms underlying motor skill learning in humans. When learning a new skill, subjects need to explore the action space in order to identify actions that lead to the maximization of their perceived ‘value’, which may take the form of a ‘reward’ (either explicit or implicit). Learning such an action-value mapping requires the exploration of the action space, until regions corresponding to a high ‘value’ are identified. At the same time, subjects need to learn actions that maximize their perceived value. Known pathological effects (with practice, performance may never improve; may even get worse) may have ‘computational’ interpretations[2].

In some situations (e.g. tool use), skill learning requires that an ‘internal model’ of the tool-and-body dynamics is acquired. This is necessary to be able to predict the ‘value’ of an intended action that involves that tool. In many cases, skill learning reduces to the acquisition of internal models. This is the case, for instance, of sensorimotor adaptation in which one subject must learn to perform a familiar task (e.g. a reaching movement) in presence of a novel, unfamiliar dynamic environment[3]. Computational studies have suggested that the acquisition of an internal model is driven by the discrepancy between actual and predicted performance (prediction error).

How to characterize skill learning? Skilled subjects are expected to increase their performance and to make it less variable. Therefore, reduced errors and reduced variability are signatures that a skill has been achieved.

B. Robot-assisted learning

How is learning affected by guidance? An appropriate guidance toward the target may lead to an earlier identification of high-value actions. If this is the case, we expect guidance to be more helpful in naïve trainees as compared to more skilled ones, and in earlier rather than later phases of learning. In contrast, in later phases of learning, when subjects are less naïve to the task, the presence of perturbations that make task performance more challenging may help reducing performance variability.

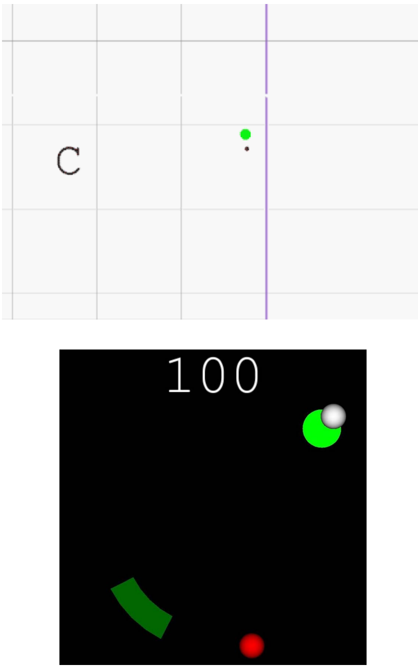

Figure 2 Screenshots of the handwriting transfer (top) and the putting tasks (bottom)

C. *How to provide guidance?*

The vast majority of guidance applications use a PD controller that closely follows a 'target' movement. Robot-assisted performance can be interpreted as a form of shared control**,** in which the goal is to transfer control from robot to human. According to this interpretation, guidance would consist of a controller that is highly specific to that particular task. In redundant tasks, the nervous system is believed to only control the task-relevant aspects of the movement (minimum intervention principle, see [4]). The robot controller should behave in a similar way, so that robot-driven movements would be similar to the actual skilled movements.

D. *Is guidance effective?*

Critics of the guidance hypothesis point out that guidance profoundly alters the dynamics of a task, so that transfer to unassisted situations might be limited. In addition, assistive forces tend to be incorporated in the motor plan, thus causing a reduction of voluntary control, which may be detrimental to learning (slacking effect [5]). Furthermore, guidance may be beneficial for some tasks, but not for others. Experiments involving the acquisition of a variety of motor skills under different assistance modalities may help to unveil the mechanisms of action of guidance, and when it is effective.

III. Materials and Methods

The experimental set-up involved a planar robotic manipulandum with two degrees of freedom – Braccio di Ferro (see **Error! Reference source not found.** for details). Subjects were seated on a chair and grasped the handle of the manipulandum. A 19" LCD computer screen, positioned at eye level about 1 m away, was used to display a virtual environment.

A. *Handwriting transfer*

In this task, we tested whether guidance could promote the intermanual transfer of handwriting skills. We focused on isolated cursive letters, and during each trial one letter was displayed on the left side of the screen; Subjects were required to reproduce it by using the manipulandum as a 'pen'; see Figure 1, top.

At the end of each writing movement, a numeric score was displayed on the screen, calculated in terms of the shape 'error'. The experiment lasted a total of four days, during which subjects practiced the generation of five cursive letters (a, c, e, g, l) with different degrees of complexity (as measured by the number of strokes). The experimental protocol was organized into epochs. During each epoch, letters were presented in a fixed sequence, in increasing order of complexity (c, e, l, a, g), two repetitions per letter. This cycle was repeated for three times (a total of 5×2×3=30 movements). On the first day, in an initial phase (dominant hand baseline, 1 epoch) subjects had to reproduce the letters that appeared on the screen by using their dominant hand. The average trajectory for each letter was used as the reference template for all subsequent epochs.

Then subjects were required to reproduce letters by using their non-dominant hand, without any assistance (non-dominant hand baseline, 1 epoch). In a subsequent phase (non-dominant hand training, 6 epochs), subjects practiced with their non-dominant hand according to several modalities of assistance (see below). Then subjects performed again without assistance (non-dominant hand after-effect, 2 epochs). The sequence of non-dominant hand movements (9 epochs in total) was repeated for the next two days, so that training lasted a total of three consecutive days. On the fourth day, subjects underwent a single non-dominant baseline phase to assess whether learning was retained.

In different groups of subjects, we tested different assistance modalities. In one subject group (control group, C) assistance was purely visual (reference template displayed in the background). In the other groups, in addition to visual assistance the robot generated assistive forces. We tested two variants of robot assistance. In the trajectory guidance (T) modality, a proportional-derivative motion controller attracted the subjects' hand toward the ongoing position of the reference trajectory. In the path guidance (P) modality, assistive force was always directed toward the closest point of the template trajectory. Both modalities of assistance follow a type of minimum intervention principle, in the sense that no force is generated if movements follow exactly the reference trajectory (T) or path (P). However, the T modality is more constraining, as it imposes not only a specific path, but also a specific timing.

A total of nineteen subjects (18M, 1F) participated in the study. All of them normally used their right hand when writing. Handedness was assessed through the Edinburgh Handedness Inventory [6]. All subjects were randomly

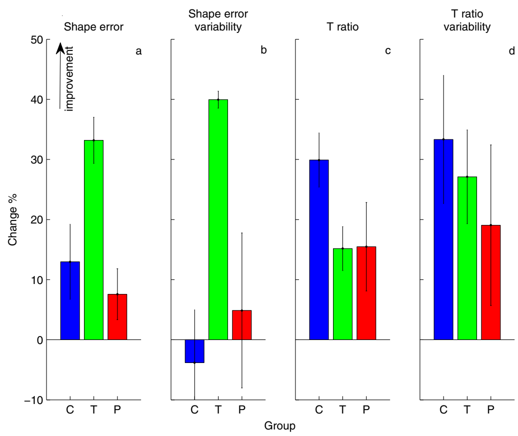

Figure 2 Percent changes of shape error and duration and their respective variability from NDb on day 1 to NDa on day 3, for the Control (C, blue), Trajectory (T, green) and Path (P, red) groups. Positive change denotes improvement

assigned to one of the three groups: control (C); trajectory guidance (T); path guidance (P).

We took shape error (figural distance between letter and reference template), movement duration and their respective standard deviations within epochs as performance measures.

B. Putting movements

In this task, subjects were required to hit a virtual ball with the handle of the manipulandum (the 'pad') in order to putt it into a target region (the 'hole'). The collision between the pad and the ball was modeled as an elastic force, which was rendered at the robot handle. The current position of the pad was continuously displayed, as a red circle (2 cm diameter) on a black background. The ball and the target were also displayed, as blue and yellow circles (diameters 2 cm and 3 cm), respectively; see Figure 1, bottom. At each trial, the hole was placed in two randomly selected directions (45° and 135°), 12 cm away from the start position. After hit, the 2-kg ball moved against a viscous force (b = 15 Ns/m). When the ball stopped, a 0-100 movement score (a function of the final ball distance from the hole) was calculated and displayed. Task performance is determined by the point of impact of the pad with the hole (it must be aligned to target direction) and by the component of the velocity of the pad just before impact that is orthogonal to ball surface. The tangential component of pad velocity at impact has no effect on performance (i.e., it is task-irrelevant). The orthogonal component of pas velocity that leads to hitting the target depends on arm inertia, and differs for different target directions.

The experiment was organized into 11 epochs, each consisting of 30 trials (a total of 330 movements). Each epoch consisted of 15 repetitions of movements in the two directions, in alternation. We tested a total of 12 subjects. In the control group (7 subjects, 3M+4F), the robot provided no assistance (only force rendering during impact with the ball). In the assisted group (5 subjects, 4M+1F), during the first 9 epochs the robot provided two types of assistance: (i) a cone-shaped virtual wall, which constrained hand movements to hit the ball in a single point, while allowing different directions of approach; (ii) a velocity controller, which set the component of ball velocity normal to the target to the magnitude required to hit the target. This value was determined through linear regression of longitudinal errors over pad velocities during the initial trials. During the assisted epochs, an adaptive controller adjusted the gain of the velocity controller and the stiffness of the virtual wall in order to keep the overall score at an approximately constant level.

We took longitudinal error and lateral (directional) error as performance measures. The former is determined by the correct selection of impact velocity (orthogonal component). The latter is solely determined by the point of impact.

IV. RESULTS

A. Handwriting transfer

The experimental results are summarized in Figure 2. After training, subjects undergoing trajectory guidance exhibited an average 34% decrease in the shape error, more than twice that observed in visual guidance subjects (13%). The difference was statistically significant ($p=0.011$). In contrast, the P group did not show statistically significant changes. These effects were substantially retained one day after the end of training. As regards shape variability, only trajectory guidance resulted in a significant decrease. Furthermore, all training modalities led to a gradual decrease of movement duration and its variability, with no significant group differences.

B. Putting

When looking at the overall task performance (target error, percentage of successful trials per epoch) in the last (unassisted) epoch, we found no significant differences in the assisted and control groups. However, when looking at longitudinal and directional errors separately, we found that subjects in the assisted group exhibited a significantly smaller longitudinal error ($p<0.02$), but no differences in the lateral error; see Figure 3. Furthermore, throughout the exercise session the fraction of successful hits was consistently lower in the assisted group than in controls, but the difference was not significant at the end of training.

V. DISCUSSION

A. Timing information is essential for handwriting transfer

We found that in the trajectory guidance (T) group the shape error reduces more, and becomes less variable than in the control (C) group. In contrast, path (P) guidance is ineffective or even detrimental. This is somehow surprising (what only matters in handwriting is shape - timing is 'task-irrelevant'). Why timing information is so important? An explanation may reside in the nature of this task. Hand dominance is believed [7] to reflect a functional specialization (the dominant hand for dynamic control, the non-dominant hand for posture and stabilization). Therefore, intermanual transfer mostly requires a fine-tuning of dynamics control of the non-dominant hand, an operation that relies on the accuracy of internal representations of body (hand) dynamics. Therefore, the task can be seen as a form of adaptation, likely driven by the prediction error; an information that is critically based on timing information. The lack of improvement through visual assistance alone is consistent with the notion that proprioception, but not vision, is essential in adapting to novel dynamic environments [8]. Likewise, Feygin et al. [9] found that haptic (trajectory) guidance is more effective than visual guidance at learning the temporal aspects of a complex movement.

B. Guidance is beneficial to learn impact velocity, but not in improving accuracy in impact position

In the putting experiment, we found that assistance may help reducing longitudinal, but not directional error. It should be noted, however, that these error components depend on two different aspects of the movement. Longitudinal error depends on speed accuracy (i.e., hitting the ball with the correct speed). Directional error depends on position accuracy (i.e. impact position). The velocity controller allows subjects to experience the correct speed, and this knowledge is transferred to non-assisted movements. In contrast, although the cone-shaped fixture constrains impact position, no transfer occurs. In fact, in position accuracy visual information is much more important than proprioception. Accuracy in a micro-manipulation task was found to improve if visual errors are magnified[10]. A similar effect was observed in presence of de-stabilizing forces (divergent force fields) [11]. In contrast, guidance cancels visual errors, therefore it may not improve visual control. Similarly, guidance was found to be useless or even detrimental in adaptation to visuomotor rotations[12]; another task in which visual errors and visual control play a crucial role.

VI. CONCLUSIONS

Our results indicate that guidance may facilitate the acquisition of some specific – but not all - motor skills. More specifically, guidance may be beneficial when dealing with dynamics control or, more in general, with the temporal aspects of movements. In contrast, guidance is of no help when position accuracy must be improved. In this case, destabilizing forces should possibly be used instead.

In both cases, assistance took the form of a proportional-derivative controller. Both controllers are task-specific, and are designed to facilitate task completion. Moreover, they only act on the task-relevant component of the task. In other words, they are based on a 'minimum intervention principle'.

In both experiments, the gain of the controllers was modulated by the learning progress. In intermanual transfer of handwriting, in which learning is very slow, a gradual decrease of assistance over days may be sufficient. In tasks

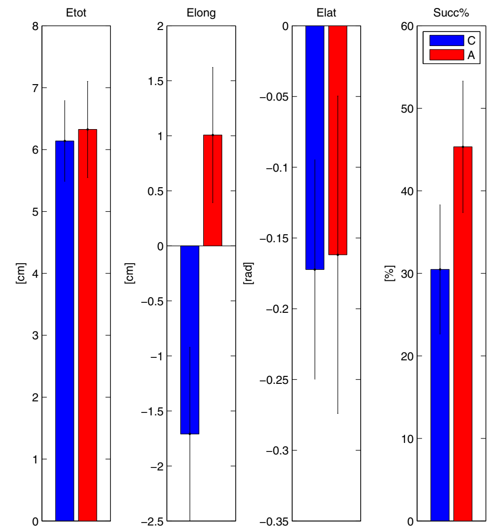

Figure 3 From left to right: final values of total error (Etot), longitudinal error (Elong), lateral error (Elat) and percent of successful hits, for control (C, blue) and assisted subjects (A, red)

like putting, continuous regulation is essential to maximize subject participation.

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