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Haptic training for a visuomotor fetch & pursue task

Pietro Morasso, Maura Casadio, and Valentina Squeri

Abstract— **Can haptic interaction improve the tracking performance in a fetch & pursue task, similar to clay pigeon shooting? In order to answer this question, we challenged the tracking movements of the subjects by a saddle-like moving force field, with the unstable manifold aligned along the moving target and the stable manifold orthogonal to it. The experimental results show a positive effect, suggesting that the internal model acquired by the subjects for compensating the target-linked haptic disturbance can improve the prediction capability of the subjects based on pure visuo-motor feedback.**

I. INTRODUCTION

Visuo-manual tracking tasks have been studied since the early 70s [1] in a variety of laboratory setups and real world skills. In particular, the mutual influence of the arm motor system and oculomotor system has been investigated in depth [2, 3] by taking into account that the visuo-motor subsystem is characterized by the interplay of two controllers, namely the saccadic and smooth pursuit eye system that integrate feedback and feed-forward mechanisms. It was found that a visual memory mechanism or memory buffer, with a duration of at least one second, operates in the planning phase of visuo-manual tasks [4], thus inducing a discontinuity in the manual control signals that are indeed characterized by intermittent step-and-hold movement periods [5, 6]. In general, there is ample evidence that constrained and accurate limb movements are composed of discrete sub-movements, as part of an intermittent error detection and correction process, although an agreement on the origin of intermittency has not yet been reached: is it the consequence of neurophysiological internal constraints [7] or of specific control strategies [8]? In any case, the single most characteristic descriptor of manual pursuit tracking patterns is the instantaneous delay between target and pursuit [9]. Only a few studies have focused on the haptic aspects of visuo-manual tracking: first of all, there is evidence that proprioception is crucial for achieving accurate performance [10] and it has been found that facilitating haptic guidance improves visuo-manual tracking performance of trajectories [11], although there is also evidence that force field adaptation can be learned using vision in the absence of proprioceptive error [12]. In another study [13] haptic interaction has a disturbing action because it implements a viscous curl field that deviates laterally the pursuit movements of an eight-shape: the results show that subjects can learn the dual task of tracking the target (although with a systematic delay) and compensating the haptic disturbance at the same time.

In this paper we consider a particular kind of tracking which resembles the task of clay pigeon shooting, i.e. aiming at a moving target, which is visible for a limited time. We designed the set-up in such a way that the target motion is predictable but prediction is hard, with uncertainly about two motion parameters: direction and curvature. For this kind of task it is not only important to minimize the tracking error but also to compensate for the systematic delay that typically characterizes continuous, persistent tracking. Assistive haptic guidance is known to improve the size of the tracking error but is ineffective for inducing the subject to anticipate the motion of the target. The haptic interaction investigated in this study attempts to induce anticipation by using an unstable, saddle-like force field, which moves with the target and has the instability manifold aligned with the instantaneous target direction. The goal was to evaluate the effectiveness of such unstable haptic interaction in improving tracking performance.

II. METHODS

A. Task & protocol

The task was to reach and track as precisely as possible the motion of a target displayed on the computer screen, placed in front of the subject (Figure 1).

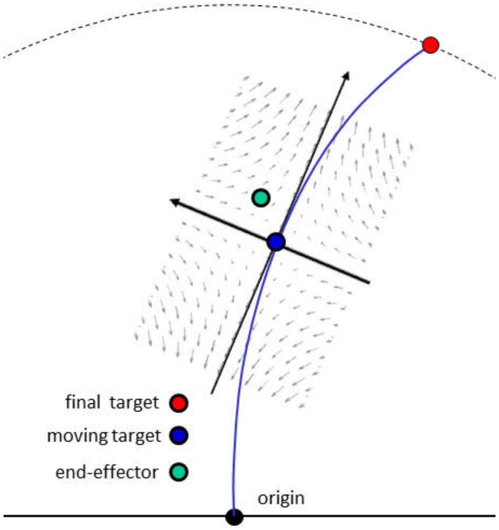

Figure 1. The saddle force field moves with the target.

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Pietro Morasso and Valentina Squeri are with the Istituto Italiano di Tecnologia, RBCS dept., via Morego 30, 16063 Genoa, Italy (phone: +39 0103991798; fax: +39 0103991798; e-mail: pietro.morasso@iit.it; valentina.squeri@iit.it).

Maura Casadio is with the University of Genoa, DIBRIS dept., Genoa, Italy (e-mail: maura.casadio@unige.it)).

All authors contributed equally to this work.

The initial position $\vec{p}_T(t_o)$ of the target was close to the chest and during each trial it moved to a final position $\vec{p}_T(t_f)$ along a circular trajectory, characterized by a radius of curvature R, with constant rotational speed and movement duration of 2s. The experimental protocol included unperturbed trials in which the subject attempted to match the target path without any opposing force and perturbed trials in which the trajectory of the hand $\vec{p}_H(t)$ was affected by the following force field (see fig. 1):

$$\vec{F}(t) = \begin{bmatrix} F_t = K_s(\vec{p}_H - \vec{p}_T) \bullet \vec{v}_t \\ F_n = K_s(\vec{p}_T - \vec{p}_H) \bullet \vec{v}_n \end{bmatrix} \qquad (1)$$

F_t and F_n are the tangential and normal components of the field, respectively, in relation with the instantaneous direction of the target trajectory; $\vec{v}_t, \vec{v}_n$ are the corresponding unit vectors; K_s=200N/m is the elastic constant of the field. F_t has a repulsive effect on the hand whereas F_n has an attractive effect. In order to avoid too high force values we imposed a saturation of force, by multiplying the force field value of eq. 1 by the gain β, computed as follows:

$$\begin{cases} Dist = \left|\vec{p}_T - \vec{p}_H\right| \\ \alpha = \dfrac{Dist - R_2}{R_1 - R_2} \\ \beta = 0 & \text{if} \quad Dist > R_2 \\ \beta = 1 & \text{if} \quad Dist < R_1 \\ \beta = 0.5(1 - \cos\alpha\pi) & \text{if} \quad R_2 \le Dist \le R_1 \end{cases} \qquad (2)$$

with R_1=0.05m and R_2=0.08m.

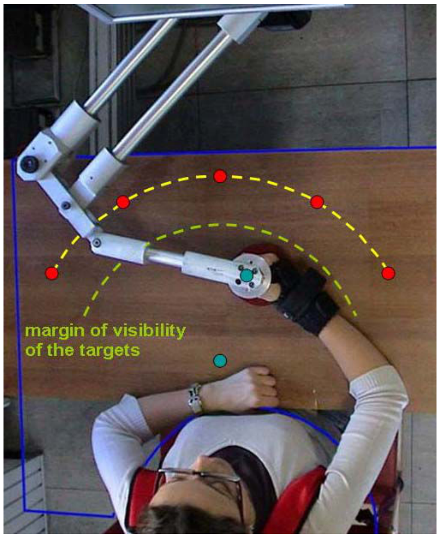

Figure 2. Experimental setup.

Each trial, from the origin to the final position of the target, included an initial wait time (variable), a movement time of 2s, a hold time in the final position; after that, the moving target reappeared on the origin (no return movements). The targets were visible for 75% of their trajectories, then disappeared and became visible again in the final position (see fig. 2).

During the experiments, we used 5 final targets, placed on a circle at a distance of 20 cm from the origin: one target in front of the subject and the other targets were rotated medio-laterally by ±30deg and ±60deg. For each target, 5 values of curvature C were used (in cm^{-1}): 0, ±1/20, ±1/11.54. For each block of trials, which included 125 movements (5 directions × 5 values of C × 5 repetitions) the order of presentation was randomized. A cycle included 25 movements: 5 directions × 5 curvatures (see figure 3). A block included 5 cycles (125 movements), with 5 catch trials (trials without field) per cycle. Therefore, at the beginning of each trial the subjects were quite uncertain of the target path they were required to fetch and track, in a similar way to clay pigeon shooting.

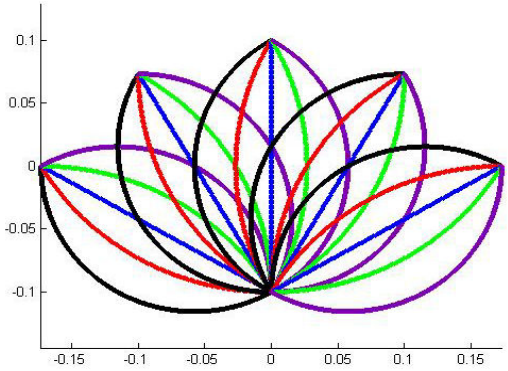

Figure 3. Visualization of the target-set (125 movements). Units: m.

The Protocol was organized as follows: *Familiarization* (Null Field *NF*): 1 block (125 movements); *Adaptation* (Force field *FF1 FF2 FF3*): 3 blocks (375 movements), with 5 catches per cycle (1 for each direction and curvature, 25 catches per block); *Wash out (WO)*: 1 block (125 movements). At the end of the adaptation phase we will have 75 catches, 15 catches per directions. A movement is considered successful if the distance between the moving target and the end-effector remains less than 1.5 cm for more than the 80% of the entire movement (T1=2s). Successful trials were rewarded with an acoustic signal.

B. Motion capture and haptic interaction

The haptic disturbance was generated by a planar manipulandum (BdF, Celin srl, La Spezia, Italy) [14]. During perturbed trials the force delivered by the manipulandum to the hand was generated in real-time according to eq. 1 and 2. During unperturbed trials the force was switched off. In both cases the trajectory of the hand was measured by means of the precision encoders of BdF.

C. Subjects

Five healthy subjects (S1-S5: 2 males, 3 females, age = 28.20±4.97 years) with no history of neurological or orthopedic disease participated in the study. All participants gave their informed consent prior to testing. The study was approved by the local ethics committee. Subjects were required to sit in front of the manipulandum, with their shoulders and wrist movements restrained by suitable holders and grabbed the end effector of the robot with their dominant hand (right hand for all the subjects except S3). The target to track and the cursor corresponding to the end effector position were shown in a computer monitor positioned about 2 m away at eye level.

D. Data analysis

As primary outcome we used the averaged *Tracking Error* (TE), i.e. the distance between the moving target and the cursor, averaged along the entire trajectory. For investigating further the effect of the force field and the related learning process we also decomposed TE into two components, in relation with the ongoing target trajectory: the *tangential component* (TAN) and the orthogonal or *lateral component* (LAT). Notice that the force field has two opposite effects in these two cases: a destabilizing effect in the former case that tends to augment the tangential component of the tracking error and a stabilizing effect in the latter that tends to reduce the lateral component of the error. We considered both the norm and the signed version of these indicators because they provide us with different information. Specifically, by looking at the tangential error we expect the cursor to follow the target (negative sign) and we want to investigate if this force can help the subject to reduce this error by inducing a better prediction of the target trajectory. Two more indicators were computed, by taking into account that in the initial part of the trajectory (75%) the subjects had full visual feedback while in the last part (25%) they pursued a memorized trajectory, without any visual feedback, except at the very end: TE with vision and TE without vision. The analysis of performance in the two situations can be indicative of the importance of continuous visual feedback in predicting the target motion.

E. Statistical analysis.

Statistical analysis was based on repeated measures ANOVA. Significant main effects were followed by post-hoc analyses (Newman Keuls test). Significance was accepted at $p<0.05$. The analysis was performed with STATISTICA 7© (StatSoft, Tulsa, OK., USA).

III. RESULTS

Figure 4 shows the evolution of the overall tracking error for the whole population of subjects (table I stores a summary of the errors). In the initial familiarization phase, the subjects required about three blocks of trials (difference between early and late baseline $p=0.001156$) in order to reach a steady performance: the averaged TE settled to a value of about 2cm (no differences in the late familiarization phase p=0.9139). After the force field was turned on, TE increased by about 50% and then gradually went back to the original performance, after 15 blocks for a total of 375 movements ($F(1,4)= 24.66, p=.00767$). In the WO phase, when the force field was turned off again, the subjects exhibited a TE which was significantly lower than at the end of the familiarization phase ($F(1,4)=10.45, p=.03189$).

The two results above suggest that not only the subjects were able to compensate the disturbing effect of the force field but also this learning process had the effect of improving their tracking performance. In other words, *haptic training* works.

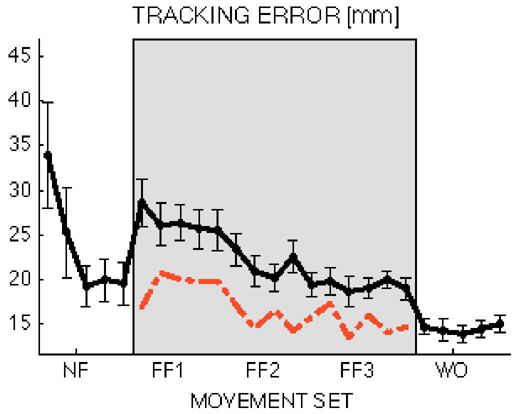

Figure 4. Black line: tracking error (mean ± SE). Red line: catch trials. NF= null field phase. FF force field phases; WO wash out phase.

This consideration is further reinforced by the analysis of the catch trials (see the red trace in fig. 4). The error is significantly better with respect to the concurrent force fields trials. Moreover, it decreases with training and in the late part, namely in FF3, it approaches the performance of the WO phase.

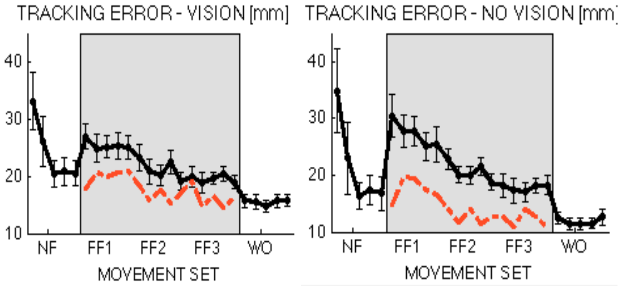

Figure 5. Tracking error (mean ± SE) with visual feedback (in the early part of trajectory) and without visual feedback (in the late part of the trajectory). Red line: catch trials. NF= null field; FF force field ; WO wash out phase.

The analysis of the movement part of the trajectory with and without visual feedback (Figure 5) confirmed this result and indicated that the error is independent of the provided visual feedback. The error in the no vision part of the trajectory was bigger with respect to the rest of the trajectory at the beginning of the NF and FF phases, suggesting that visual feedback is critical when a new task of this kind is addressed. However, at the end of the FF phase, when subjects mastered the dynamics of the force field, there is no difference in TE with and without visual feedback. Moreover, it is somehow surprising that during wash out our well trained subjects performed better without than with visual feedback. This suggests that improvements in the prediction of the target motion facilitated by haptic training are such that subjects do not use any more visual feedback in the final part of the *shooting*.

The analysis of the tangential and orthogonal component of the tracking error provided further information about the effect of haptic training on tracking performance.

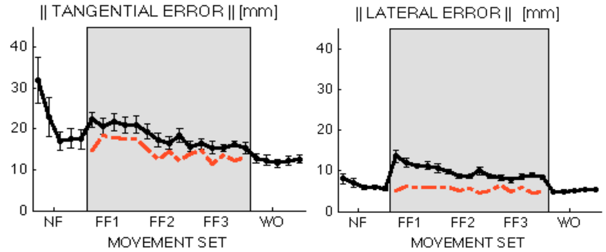

Figure 6. Absolute value of tangential and lateral components of the tracking error (mean ± SE). Red line: catch trials; NF= null field;. FF= force field ; WO wash out.

Fig. 6 plots the evolution of the absolute value of TE and fig. 7 the evolution of the corresponding signed values. The plot in the former case has the same time course of the overall TE. The tangential component is bigger than the lateral component since the beginning; moreover, these indicators clearly show that improvement of tracking performance during WO is due more to the tangential error (significant) than the lateral error (not significant). Notice that the force field has two opposite effects in these two cases and subjects showed a more evident performance improvement where the field has a destabilizing effect than where it has a stabilizing effect.

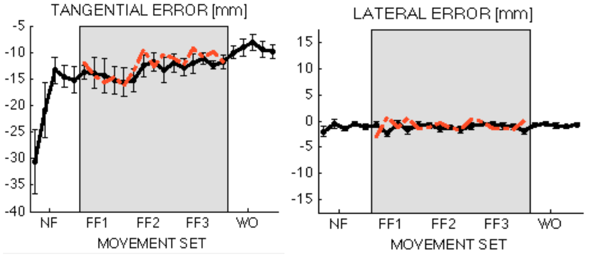

Figure 7. Tangential and lateral components of the tracking error (mean ± SE), including sign. component of the tracking error. Red line: catch trials; NF= null field;. FF= force field ; WO wash out..

If we take into account the sign of the TE (fig. 7) we see that the tangential component is always negative, which denotes a delay of the tracking movements, but such deficiency of prediction is greatly reduced over training. The lateral component of the error remains small (about 1mm), with a very small bias and is not influenced much by the proceeding of the training.

IV. DISCUSSION

In summary, we think that the question formulated at the beginning of this study (*Can haptic interaction improve the tracking performance in a fetch & pursue task*?) can be answered positively. In our opinion, the crucial aspect of the phenomenon is the challenge posed to the subjects by the longitudinal, unstable component of the force field. We speculate that this challenge might have two main positive effects: 1) a generic "*attention effect*", in the sense that the force field induced the subjects to focus their attention on the tangential component of the task; 2) a *metric effect,* because the perceived force feedback reinforced the visual evaluation of the tracking error, providing crucial metric information for building an internal prediction model of the movements of the target in the specific task. In general, we suggest that the role of haptic training, in improving the task performance, is just another example of what has been described as the tendency of the brain to behave as a *greedy optimizer of error and effort* [15]. Moreover, these results support the hypothesis that that haptic error augmentation can be beneficial for improving performance not only in reaching [16,17], but also in tracking tasks.

TABLE I: summary of tracking errors [mm]

	Middle NF	**Late NF**	**Early WO**	**Late WO**
TE	19.25±5.03	19.56±5.40	14.71±2.06	14.98±2.26
TAN	-13.36±5.45	-15.16±5.58	-10.01±2.55	-9.85±3.12
|TAN|	16.96±4.98	17.50±5.21	12.80±2.23	12.60±2.28
LAT	-1.39±0.81	-1.12±1.30	-0.68±0.82	-0.71±0.76
|LAT|	5.97±1.08	5.63±1.29	4.79±0.37	5.40±0.52

Mean±std over 25 trials.

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