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RESEARCH ARTICLE

Submovement Organization, Pen Pressure, and Muscle Activity Are Modulated to Precision Demands in 2D Tracking

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ABSTRACT. The authors investigated how tracking performance, submovement organization, pen pressure and muscle activity in forearm and shoulder muscles were affected by target size in a 2D tracking task performed with a pen on a digitizer tablet. Twenty-six subjects took part in an experiment, in which either a small dot or a large dot was tracked, while it moved quasirandomly across a computer screen at a constant velocity of 2 cm/s. The manipulation of precision level was successful, because mean distance to target and the standard deviation of this distance were significantly smaller with the small target than with the large target. With a small target, subjects trailed more behind the center of target and used submovements with larger amplitudes and of shorter duration, resulting in higher tracking accuracy. This change in submovement organization was accompanied by higher pen pressure, while at the same time muscle activity in the forearm extensors and flexors was increased, indicating higher endpoint stability. In conclusion, increased precision demands were accommodated by both a different organization of submovements and higher endpoint stability in a 2D tracking task performed with a pen on a digitizer tablet.

Keywords: manual tracking, motor control, muscle activity, neuromotor noise, upper extremity

Every day tasks such as threading a needle, buttoning up your shirt, writing, or working with a computer keyboard or mouse require positional precision of the end-effectors (i.e., hands or input device). The positional precision of the end-effector is limited, because motor control is a noisy process in which force variability causes kinematic variability (Harris & Wolpert, 1998). In order to meet precision requirements in the task, this kinematic variability of the system needs to be decreased or filtered. Because neuromotor noise is signal-dependent (i.e., it increases with the magnitude of the motor command), the noise can be decreased by reducing movement speed, thus allowing higher positional precision (Harris & Wolpert, 1998). This is reflected in Fitts' law, which predicts longer movement times with increased task difficulty (Fitts, 1954). However, reduction of movement velocity is not a feasible option in all motor tasks. In case high precision is required in a task with fixed movement times, kinematic variability can be filtered or suppressed by increasing mechanical stiffness, or resistance to displacement of the moving limb (Burdet, Osu, Franklin, Milner, & Kawato, 2001; Gribble, Mullin, Cothros, & Mattar, 2003; Laboissiere, Lametti, & Ostry, 2009; Lametti, Houle, & Ostry, 2007; Wong, Wilson, Malfait, & Gribble, 2009). Limb stiffness can be increased by increasing the level of cocontraction of the agonist and antagonist muscles (Selen, Beek, & van Dieen, 2005). In addition, Van Galen and De Jong (1995) suggested that in case the end-effector is in contact with the environment, stability in the endpoint can also be increased by increasing the friction between the end-effector and the substrate. In their studies, in which positional precision of a pen on the surface was required, axial pen pressure was shown to increase with increasing task complexity (Van den Heuvel, van Galen, Teulings, & van Gemmert, 1998).

The use of the previous strategies to stabilize the end-effector in response to increased precision demands requires increased muscle activity, which seems paradoxical because of the signal-dependency of the neuromotor noise. Increased muscle activity would imply increased force variability, and thus kinematic variability. However, in a modeling study by Selen, Beek, & van Dieen (2005) it has been shown that increased cocontraction levels can lead to a decrease of movement variability, despite the increase in neuromotor noise. In addition, Missenard and Fernandez (2011) found in an experimental study that with higher levels of muscle cocontraction, higher movement accuracy could be reached at similar movement speeds. This is in line with experimental evidence for increased cocontraction levels with smaller targets, which has been found in time-constrained aiming tasks (Gribble et al., 2003; Laursen, Jensen, & Sjogaard, 1998; Osu et al., 2004; Sandfeld & Jensen, 2005; Visser et al., 2004). Direct estimates of elbow stiffness and damping, obtained by applying torque perturbations to the arm during aiming movements, were increased with smaller targets (Selen, Beek, & van Dieen, 2006). However, no effect was found of precision demands on pen pressure in graphical aiming (Van Galen & Van Huygevoort, 2000). It may be that in aiming tasks, in which precision is only required in a small part of the task, friction with the environmental substrate is not used to increase external stability.

Tracking tasks may be more suitable than aiming tasks to explore the strategies to stabilize the end-effector in response to precision demands. In tracking, the degrees of freedom are more limited, because instantaneous movement velocity of the end-effector is constrained and positional accuracy is required continuously. However, the evidence for increased

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cocontraction with precision demands in tracking tasks is scarce. Joint stiffness during single-joint elbow tracking was found to be higher with higher precision demands (Selen, van Dieen, & Beek, 2006). However, in addition to increasing stiffness, subjects changed the organization of their submovements. Oscillations in the velocity profile are seen as numerous submovements of tracking. Submovements were quantified according to the fluctuations in the speed profile, with the slope between the amplitude of the speed pulses and their duration defined as the speed pulse gain. With smaller targets, submovement gain was found to be higher, as a result of larger submovement amplitudes with invariant duration. This most likely reflects faster error corrections enabling the subject to stay closer to the center of target. However, another movement strategy was found in a study by Selen, Beek, and van Dieen (2007), when neuromotor noise was increased by inducing fatigue. With fatigue, subjects maintained their percentage time on target, despite the larger kinematic variability, by reducing the percentage of time that was spent behind the center of the target. This suggests use of a feed-forward strategy. Moving closer to the center of target was most likely possible because the target trajectory was predictable. It is possible that stiffness regulation would have been used when the target followed an unpredictable trajectory and using a feed-forward strategy was not possible.

Because single-joint tracking tasks are strongly constrained it can be questioned whether the findings of these studies (Selen, Beek, et al., 2007; Selen, van Dieen, et al., 2006) can be generalized to less artificial, multidirectional tracking tasks in which multiple degrees of freedom are available. Increased muscle activity would probably be required throughout the limb to increase limb stiffness and to increase pressure on the substrate, making these stabilizing strategies energetically costly. In multidirectional tracking with a computer mouse, no effects of precision demands on muscle activity levels were found (Visser, De Looze, De Graaff, & Van Dieen, 2004). It is unsure whether changes in submovement organization or a feed-forward strategy were applied with a smaller target, as these measures were not collected in that particular study. It is possible that in multidirectional, multijoint tracking tasks, with more degrees of freedom, alternative strategies predominate and strategies to stabilize the end-effector, either through cocontraction or increased friction with the substrate, are not used.

Therefore, in the present study, we aimed to investigate how tracking performance, submovement organization, muscle activity in the forearm and shoulder muscles, pen pressure, and perceived exertion were affected by target size in a 2D tracking task performed with a pen on a digitizer tablet. To prevent feed-forward strategies, in the present study an unpredictable target trajectory was used. We hypothesized that in this multidirectional tracking task stabilizing strategies of the system, either increasing muscle activity or pen pressure would not be used in response to increased precision demands and that changes in submovement organization would predominate. More specifically, in line with Selen, van Dieen, et al. (2006), an increase of submovement gain was expected with increased precision demands.

Method

Subjects

Subjects were 26 subjects (4 men and 22 women; *M* age = 42.4 years, *SD* = 10.7 years; *M* height = 173.1 cm, *SD* = 8.7 cm; and *M* weight = 65.7 kg, *SD* = 7.5 kg). All subjects were right-hand dominant and had normal or corrected-to-normal vision. None of the subjects reported symptoms in the neck, shoulders, or arms in the previous year, or had a history of musculoskeletal disorders in the neck or upper extremities. Prior to participation, subjects signed an informed consent. The study was approved by the Medical Ethics Committee of the VU University Medical Center.

Procedure

Subjects performed a tracking task with a pen on a digitizer tablet while looking at a computer screen. Seat height and screen height were adjusted to the anthropometrics of the subject, to ensure that subjects sat with a knee angle of 90°, feet flat on the ground, upper arms vertical with relaxed shoulders, and elbows flexed 90°. The forearm was supported by the armrests of the chair. The tablet was placed in front of the subject, with the lower side at the edge of the table and the midline of the tablet corresponding to the midline of the subject. The top of the computer screen was placed at eye height (Figure 1).

The task consisted of tracking a target dot, which moved quasirandomly across part of the computer screen with a constant velocity of 20 mm/s. Subjects were instructed to keep the cursor (dot with a diameter 1.9 mm) positioned as well as possible within the target dot by moving the pen on the tablet. The pen movement corresponded one to one with the

FIGURE 1. Picture of a subject in the experimental setup.

cursor movement on the screen. Subjects started with performing four practice trials of 1 min each with a target dot of 12.8 mm in diameter. Between the practice trials subjects rested for at least 3 min to prevent fatigue. Then subjects performed four tracking trials with a duration of 2 min, two trials with a small target dot (ST, diameter 6.4 mm), the high-precision condition, and two trials with a large target (LT, diameter 19.2 mm), the low-precision condition. A different target trajectory was used for the experimental trials and the practice trials, to prevent subjects from recognizing the trajectory after several trials. For the experimental trials, the same trajectory was used, because the level of precision that can be achieved seems to be dependent on factors such as location, posture, and movement direction (Brouwer & Farris, 2007; Brouwer, Mazzoni, & Pearce, 2001; Fernandez & Bootsma, 2004; Lametti & Ostry, 2010). Therefore, it appears that the level of difficulty cannot be fully standardized in random trajectories. Subjects were encouraged to explore different working techniques during the practice trials, for instance keeping their writing hand on the tablet or not, but were instructed to apply only their preferred technique during the experimental trials.

The order of the tracking trials was balanced across subjects, choosing one of the following orders: ST LT ST LT; ST LT LT ST; LT ST LT ST; or LT ST ST LT. In between the trials at least 5 min of rest was taken to prevent fatigue.

Data Acquisition and Analysis

Tracking Performance

The tracking task was programmed in LabVIEW (National Instruments Corporation, Austin, TX). The trajectory is presented in Figure 2. The target moved within a window of 0.16 m high and 0.22 m wide on the computer screen. Horizontal and vertical position of the pen on the tablet (Intuos A4, Model: GD-0912-R, WACOM Europe, GmbH, Krefeld, Germany) were measured with a spatial accuracy of 0.25 mm, at a sample frequency of 100 Hz. After low-pass filtering the horizontal and vertical position of the pen (fourth-order Butterworth filter with a cutoff frequency of 12 Hz), the following measures were calculated using MATLAB (The MathWorks, Natick, MA):

1. Percentage time on target (%TT), the percentage of the total number of samples for which the cursor was completely within the target.
2. Mean distance to target (MDT), mean distance between the center of the target and the center of the cursor.
3. Standard deviation of distance to target (SDDT), the standard deviation of the distance between the center of the target and the center of the cursor.
4. Percentage lag (%lag), the percentage of the total number of samples for which the center of the cursor was behind the midline of target. First, all data points were aligned with the movement direction of the target, and then a line through the center of the target was drawn (the line through the center of target perpendicular to the target movement direction). For all cursor data points it was determined whether it was in front or behind the midline through target, with 100% lag meaning that the cursor was always behind the middle half of the target and (e.g., 10% lag meaning that the cursor was 10% of the time behind the midline of target and 90% of the time ahead of the middle half of the target).

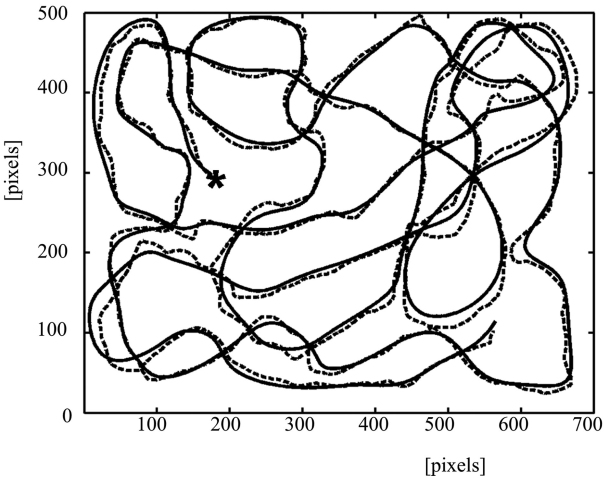

FIGURE 2. Tracking trajectory of the experimental trials is shown with the solid line. An example of the position of the cursor is presented by the dashed line.

Submovement Organization

The oscillations in the velocity profile are seen as numerous submovements of tracking. These submovements were analyzed similarly to Roitman, Massaquoi, Takahashi, and Ebner (2004), Pasalar, Roitman, and Ebner (2005), and Selen, van Dieen, et al. (2006). Before differentiating the position signals, these were low-pass filtered using a fifth-order Butterworth filter with a cutoff frequency of 5 Hz. Then the following measures were calculated:

1. Mean duration of a speed pulse (SP duration), duration of a single speed pulse is the time between two successive local minima in the velocity profile (Figure 3).
2. Mean amplitude of a speed pulse (SP amplitude), the amplitude of a single speed pulse is the difference between a local maximum in the velocity profile and the average value of the two nearest minima (Figure 3).
3. Speed pulse gain (SP gain), the slope of the linear regression between SP durations and SP amplitudes.

The cutoff frequency of 5 Hz was chosen because at this frequency the median frequency of the velocity signal corresponded best with the calculated median SP duration. Speed pulses that were too short to be actual speed pulses were in this way excluded from the analysis.

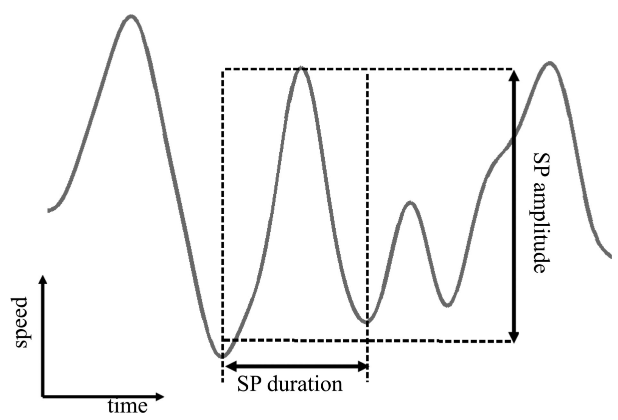

FIGURE 3. Section of the velocity profile, showing the speed pulses. The amplitude (SP amplitude) and duration (SP duration) of a single speed pulse are indicated.

Muscle Activity and Pen Pressure

As indicators of endpoint stability we studied the level of pen pressure and upper extremity muscle activity.

Axial pressure of the pen on the tablet was measured at a tip activation pressure of 0.3 to 4 N, with a sensitivity of 0.0036 N, at a sample frequency of 100 Hz, and the result was averaged over the 2-min trial.

Muscle activity was assessed of eight muscles in the neck and upper extremities:

- M. extensor carpi radialis right (ECRr) and left side (ECRl);
- M. flexor carpi radialis right (FCRr) and left side (FCRl);
- M. deltoideus pars clavicularis right side (DCr);
- M. deltoideus pars acromialis right side (DAr);
- M. trapezius pars descendens right (TDr) and left side (TDl).

To measure muscle activity, bipolar Ag/AgCl surface electrodes (Blue Sensor, Ambu®, Glen Burnie, MD, gel-skin contact area of 1 cm^2), were positioned on the muscle bellies, according to the locations described by Basmajian (1989) with an interelectrode distance of 25 mm, after shaving of hair, skin abrasion, and cleaning the skin with alcohol. Location of the electrodes was confirmed by palpation of the muscle, while the subject performed a contraction against manual resistance (i.e., dorsal flexion and radial abduction of the wrist (ECRr and ECRl), palmar flexion and radial abduction of the wrist (FCRr and FCRl), anteflexion of the arm (DCr), abduction of the arm (DAr), and lifting the shoulders (TDr and TDl)). A reference electrode was placed on the C7 spinous process. Electromyographic (EMG) signals were amplified 20 times (Porti-17, TMS, Enschede, the Netherlands; input impedance $> 10^{12}\ \Omega$, CMRR > 90 dB), band-pass filtered (10–400 Hz), and A-D converted (22 bits) at a sample rate of 1,000 samples/s. EMG signals were full-wave rectified and low-pass filtered at 5 Hz (fourth-order Butterworth) using MATLAB (The MathWorks).

For the EMG signals the Amplitude Probability Distribution Function (APDF) was calculated. Subsequently, three percentiles were used to express the static level (P10), the median level (P50), and the peak level (P90; Jonsson, 1988).

Perceived Exertion

After each tracking task, subjects were asked to rate their perceived mental exertion and their physical exertion in the upper body, using the Borg scale. The Borg scale is a 10-point scale with ratio properties ranging from 0 "not at all demanding" to 10 "very, very demanding" (Borg, 1982).

Statistical Analysis

Two-way multivariate analyses of variance (MANOVAs; Target Size [2] × Trial [2]) for repeated measures were used to test the effect of target size and trial on tracking performance (i.e., %TT, MDT, SDDT, and %lag), submovement organization (i.e., SP gain, SP amplitude, and SP duration), stability (pen pressure and muscle activity of the eight muscles), and on perceived exertion (i.e., perceived mental and physical exertion). Furthermore, the effects of target size (2) and time (2) on tracking performance, submovement organization, stability and perceived exertion variables separately were tested using univariate analyses of variance (ANOVAs); p values smaller than .05 were considered statistically significant. Effect size statistics were presented using generalized eta-squared ($\eta_G{}^2$), which is preferred to eta-squared and partial eta-squared because it provides comparability across between-subjects and within-subjects designs. A generalized eta-squared of .2 can be considered as small, .13 as medium, and .26 as large (Bakeman, 2005).

Results

Tracking Performance

A MANOVA for repeated measures showed significant overall effects of target size and trial on tracking performance (Table 1). Also, the interaction effect of target size and trial on tracking performance was significant. A univariate ANOVA revealed that when tracking the smaller target, subjects spent a significantly less time with the cursor within target (i.e., %TT) than when tracking the larger target (Tables 1 and 2). MDT and SDDT were both significantly smaller with the smaller target. The time that subjects spent behind the midline of the target (%lag) was significantly larger with the smaller target ($M = 83\%$, $SD = 6\%$) of the time, as opposed to the time with the larger target ($M = 75\%$, $SD = 10\%$).

The univariate ANOVAs also showed that all tracking performance measures were significantly affected by trial. In the first trial %TT was significantly smaller and MDT, SDDT, and %lag were significantly larger than in the second trial. Only for %TT a significant interaction effect of target size

TABLE 1. Statistical Results of the Effects of Target Size and Trial on Tracking Performance and Submovement Organization

	Target size			Trial			Target Size × Trial		
	F	*p*	η_G^2	*F*	*p*	η_G^2	*F*	*p*	η_G^2
MANOVAs									
%TT, MDT, SDDT, %lag	238.298	.000*		8.609	.000*		6.756	.001*	
SP gain, amplitude and duration	42.039	.000*		20.740	.000*		3.116	.046*	
Univariate ANOVAs									
%TT	882.072	.000*	.940	26.421	.000*	.028	15.713	.001*	.022
MDT	66.402	.000*	.300	15.464	.001*	.029	0.071	.792	.000
SDDT	91.849	.000*	.420	7.233	.013*	.014	1.004	.326	.003
%lag	18.974	.000*	.182	7.037	.014*	.017	1.649	.211	.005
SP gain	61.972	.000*	.231	17.086	.000*	.026	7.593	.011*	.013
SP amplitude	125.155	.000*	.231	45.604	.000*	.028	2.061	.163	.002
SP duration	23.235	.000*	.089	14.360	.001*	.024	0.002	.969	.000

Note. Generalized eta-squared (η_G^2) is given as a measure of effect size. For ANOVA, *df*s = 1, 24; for MANOVA, *df*s = 4, 21. ANOVA = analysis of variance; MANOVA = multivariate analysis of variance; MDT = mean distance to target; SDDT = standard deviation of the distance to target; SP = speed pulse; %TT = percentage time on target.
*$p < .05$.

and trial was found. This interaction effect seemed to be caused by a ceiling effect. With the smaller target, %TT increased in the second trial, while with the larger target in the first trial the maximum score of 100% was already approached, leaving little room for improvement in the second trial.

Submovement Organization

Organization of the submovements was significantly affected by target size and trial as shown with MANOVA for repeated measures (Table 1). The interaction effect of target size and trial was also found to be significant for submovement organization.

Follow-up analyses with univariate ANOVAs showed that the SP gain was significantly larger with a smaller target, due to a significantly larger SP amplitude and a significantly shorter SP duration (Tables 1 and 2). This means that subjects made submovements with larger and shorter speed pulses when tracking a smaller target. It was found that the SP gain was significantly lower in the second trial than in the first trial, due to a significantly smaller SP amplitude and a significantly longer SP duration. The interaction effect for target size and trial only reached significance for SP gain.

TABLE 2. Mean and Standard Deviations (*N* = 26) of Tracking Performance and Submovement Organization of Tracking the Small and the Large Targets in the First and Second Trials

	Small target				Large target			
	Trial 1		Trial 2		Trial 1		Trial 2	
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Tracking performance								
%TT	45.49	9.30	49.95	9.36	99.24	1.14	99.55	0.54
MDT (cm)	0.26	0.03	0.24	0.03	0.31	0.05	0.29	0.04
SDDT (cm)	0.13	0.01	0.12	0.01	0.16	0.03	0.16	0.02
%lag	83.39	5.11	82.31	7.79	76.62	9.90	73.25	10.42
Submovement organization								
SP gain (cm/s^2)	5.215	1.169	4.666	1.138	3.906	0.923	3.811	0.729
SP amplitude (cm/s)	1.609	0.282	1.496	0.274	1.291	0.285	1.223	0.258
SP duration (s)	0.350	0.032	0.358	0.029	0.368	0.025	0.376	0.029

Note. MDT = mean distance to target; SDDT = standard deviation of the distance to target; SP = speed pulse; %TT = percentage time on target.

TABLE 3. Statistical Results of the Effects of Target Size and Trial on Pen Pressure and Muscle Activity

	Target size			Trial			Target Size × Trial		
	F	p	η_G^2	F	p	η_G^2	F	p	η_G^2
MANOVA									
Pen pressure and 8 muscles measured	4.732	.003*		2.507	.052		1.298	.311	
Univariate ANOVAs									
Pen pressure	14.054	.001*	.169	6.055	.021*	.043	0.080	.799	.000
ECRr	21.943	.000*	.299	3.609	.069	.034	0.021	.887	.000
ECRl	17.461	.000*	.161	6.193	.020*	.093	8.350	.008*	.077
FCRr	14.795	.001*	.231	6.727	.016*	.034	0.300	.589	.002
FCRl	6.044	.021*	.077	3.359	.079	.034	0.343	.563	.004
DCr	0.189	.668	.001	3.839	.061	.038	0.153	.699	.001
DAr	4.276	.049*	.044	2.792	.107	.012	0.691	.414	.002
TDr	1.545	.255	.019	0.822	.373	.004	2.333	.139	.011
TDl	2.856	.103	.027	0.003	.960	.000	1.867	.184	.020

Note. Generalized eta-squared (η_G^2) is given as a measure of effect size. For ANOVA, *df*s = 1, 24; for MANOVA, *df*s = 9, 16. ANOVA = analysis of variance; MANOVA = multivariate analysis of variance.
*$p < .05$.

With the small target, the SP gain decrease in the second trial was larger than with the large target. This seems to be in line with the interaction effect on%TT and is most likely also caused by a ceiling effect with more room for improvement with the small target in the second trial. In the submovement analysis, a fifth-order Butterworth filter with a cutoff frequency of 5 Hz was chosen to avoid spurious speed pulse detection. However, for cutoff frequencies of 4 or 6 Hz similar statistical effects were found.

Pen Pressure and Muscle Activity

MANOVA for repeated measures showed a significant main effect of target size on measures of stability (pen pressure and muscle activity in eight muscles) and the effect of trial was nearly significant ($p = .052$; Table 3). The interaction effect of target size and trial was not significant for stability ($p = .311$).

Univariate ANOVA showed that when tracking a small target, subjects produced significantly higher pen pressures than when tracking a large target (Table 3 and Figure 4). Pen pressure was also significantly affected by trial, in the second trial pen pressure was significantly lower than in the first trial. No interaction effect of target size and trial was found for pen pressure.

Muscle activity levels P10, P50, and P90 showed similar results. Therefore only the P50 results are reported. For a small target, muscle activity in the ECRr, ECRl, FCRr, FCRl, and DAr was significantly higher than for the large target. For the DCr, TDr, and TDl no significant effects of target size were found (Table 3 and Figure 5). Only for the ECRl and FCRr was a significant effect of trial was found, indicating that the muscle activity in the second trial was significantly lower than in the first trial. A significant interaction effect of target size and trial was found for ECRl, indicating that subjects lowered their muscle activity in the ECRl in the second trial as compared to the first trial for the small target, whereas the muscle activity in the second trial for the large target remained more or less the same as in the first trial.

Perceived Exertion

MANOVA for repeated measures showed significant main effects of target size and trial on perceived exertion

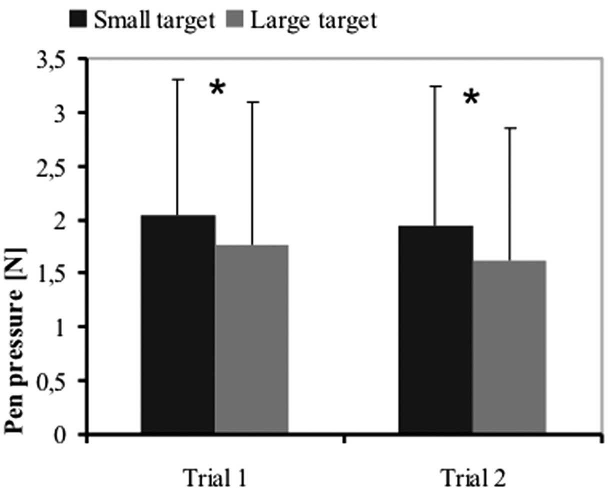

FIGURE 4. Mean and standard deviation (error bars) of the pen pressure are shown for both trials for the small and for the large target.

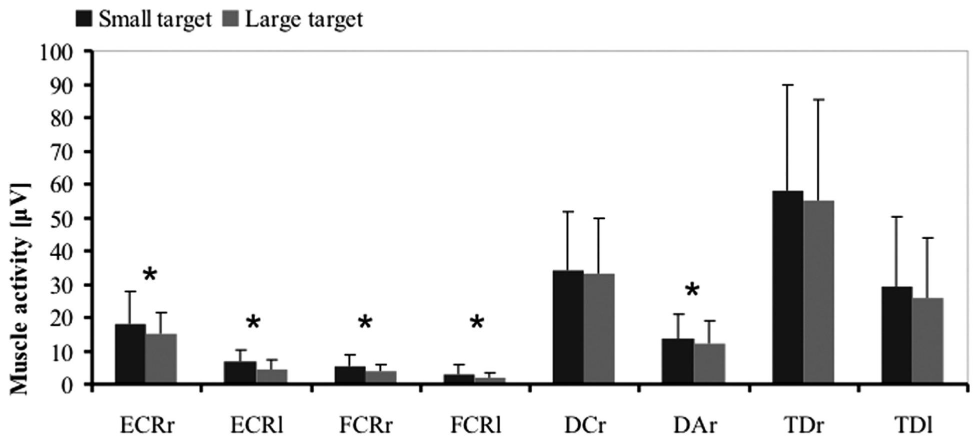

FIGURE 5. Muscle activity in the eight muscles; M. extensor carpi radialis right (ECRr) and left side (ECRl), M. flexor carpi radialis right (FCRr) and left side (FCRl), M. deltoideus pars clavicularis right side (DCr), M. deltoideus pars acromialis right side (DAr), M. trapezius pars descendens right (TDr) and left side (TDl). For the small and large targets the mean and standard deviation (error bars) of both trials are given.

(Table 4). The interaction effect of target size and trial was not significant for perceived exertion. Follow-up analyses with univariate ANOVAs revealed that both perceived mental exertion and perceived physical exertion were rated significantly higher when tracking the smaller target (see Table 4 and Figure 6) and in the first trial as compared with the second trial.

Discussion

In the present study, we aimed to investigate how tracking performance, submovement organization, muscle activity in eight shoulder and forearm muscles, and pen pressure were affected by target size when subjects performed a 2D tracking task with a pen on a digitizer tablet. In line with the hypothesis we found that with smaller targets subjects changed their submovement organization toward larger submovements with shorter duration. In contrast with the hypothesis, we found that subjects also increased their pen pressure and muscle activity, when tracking a smaller target.

With the larger target, MDT was slightly, but significantly, larger than with the smaller target. This indicates that subjects accepted a larger distance from the center of target, which is in line with several earlier studies (Osu et al., 2004; Selen, van Dieen, et al., 2006; Visser et al., 2004) that all found a smaller distance to the middle of target when tracking smaller targets. However, subjects only increased their MDT slightly, while the larger target provided much more space, which seems to indicate that subjects adopted a different strategy. This was also indicated by the fact that with a smaller target, subjects showed a smaller variation of MDT (SDDT), and subjects spent more time behind the middle half of target (%lag). Subjects probably trailed more behind the center of the target in the small target condition to allow for more visual information on the direction the target was moving into. In general, effect sizes for tracking

TABLE 4. Statistical Results of the Effects of Target Size and Trial on Perceived Mental and Physical Exertion

	Target size			Trial			Target Size × Trial		
MANOVA	*F*	*p*	η_G^2	*F*	*p*	η_G^2	*F*	*p*	η_G^2
Perceived mental and physical exertion	19.391	.000*		4.557	.023*		0.233	.794	
Univariate ANOVAs									
Perceived mental exertion	28.369	.000*	.158	7.828	.010*	.031	0.138	.713	.000
Perceived physical exertion	17.892	.000*	.095	6.633	.016*	.006	0.381	.542	.000

Note. Generalized eta-squared (η_G^2) is given as a measure of effect size. For ANOVA, *df*s = 1, 24; for MANOVA, *df*s = 2, 21. ANOVA = analysis of variance; MANOVA = multivariate analysis of variance.
$^*p < .05$.

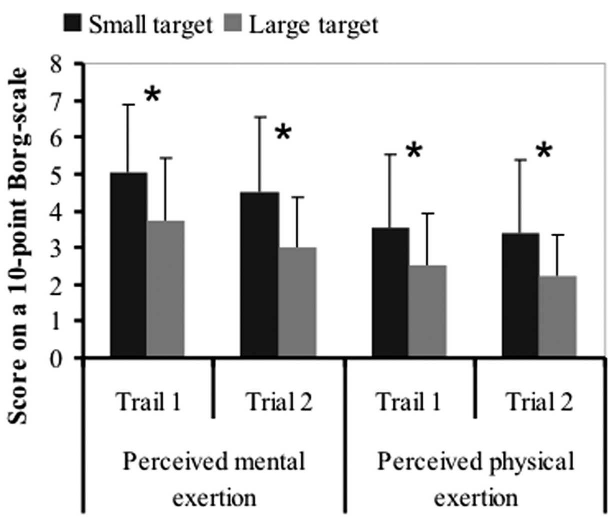

FIGURE 6. Mean and standard deviation (error bars) of perceived mental exertion and perceived physical exertion rated on a 10-point Borg scale in the two trials for the small and large targets.

performance outcome measures were large, with generalized eta-squared being above .30. The effect size of %lag was the lowest with 0.18, which can still be considered a medium to large effect.

In line with our hypothesis, SP gain was significantly larger with the small target as compared with the large target caused by larger SP amplitudes and shorter SP durations. Selen, van Dieen, et al. (2006) also found higher SP gain and SP amplitudes with smaller targets. However, they did not find changes in SP duration. Similarly, in the studies by Pasalar et al. (2005) and Roitman et al. (2004), different tracking velocities led to changes in SP gain and SP amplitude, but not to changes in SP duration. Hence, a constant SP duration was found in these previous studies, in contrast to the present study, which may have been due to the fact that these previous studies all used cyclic and thus predictable target trajectories. Another reason may be that in the study of Selen, van Dieen, et al. (2006), the difference in target sizes was not as large as in the present study. Finally, previous studies may have lacked statistical power, because small numbers of subjects were tested and the effects of precision demands on SP duration found in the present study were small. Intermittency of tracking, as evident with the detection of submovements, seems to be highly dependent on visual feedback allowing comparison of the target and cursor position. For example, depriving the subject of visual feedback (Miall, Weir, & Stein, 1993) or increasing distance between visual feedback of the target and the cursor (i.e., separation of cues; Reed, Liu, & Miall, 2003) led to smoother tracking. Our data thus underscore the importance of feedback modulation in response to changes in precision demands.

The question remains whether subjects not only changed their movement kinematics but also simultaneously increased their muscle activity and pen pressure. In contrast to our hypothesis, we found higher pen pressure with higher precision demands, which implies the need for higher endpoint stability. Visser et al. (2004) did not find an effect of precision demands on grip forces on the computer mouse during tracking. However, grip forces on the mouse are not necessarily related to pressure of the mouse on the environmental substrate. In aiming tasks, pen pressure has been shown to be affected by time pressure and mental load, but not by precision demands (Van Galen & Van Huygevoort, 2000). However, in graphical aiming, precision is only required at the endpoint. Consequently, stability in the endpoint may be increased only in the last phase of the movement (Osu et al., 2004) and pen pressure averaged over the whole movement would not necessarily reveal such an effect.

Indications for higher cocontraction were found in the fact that muscle activity in the antagonistic pair, ECR and FCR, in the dominant arm was increased with precision demands. This is in line with previous studies that found higher precision levels with higher muscle cocontraction in goal-directed movements (Missenard & Fernandez, 2011), higher cocontraction levels with smaller targets in time constrained aiming (e.g., Gribble et al., 2003; Osu et al., 2004; Sandfeld & Jensen, 2005; Visser et al., 2004) and higher stiffness and damping levels with higher precision demands in single joint tracking (Selen, van Dieen, et al., 2006). Visser et al. (2004) found no indications for increased antagonistic cocontraction with high-precision tracking. Only a tendency toward increased forearm flexor activity was found with high precision, while forearm extensor activity was unaffected. Although higher cocontraction will generally increase stiffness of the limb, this may not necessarily be its primary aim. In the present study, the higher muscle activity could be related to the higher pen pressure, as in handwriting grip force in the pen and normal force to the surface appear to be correlated (Chau, Ji, Tam, & Schwellnus, 2006), and higher grip forces imply higher forearm muscle activity. Alternatively, the higher muscle activity could be related to the faster corrective movements that were found with higher precision demands. However, even if the primary aim of the cocontraction was to increase stiffness of the limb, the absolute increase in muscle activity was small, which may not be surprising for a multijoint and multidirectional tracking task. Usually, the orientation of maximal limb stiffness aligns with the direction requiring greatest special accuracy and in the direction of the mechanical instability (e.g., Franklin et al., 2007; Lametti et al., 2007; Selen, Franklin, & Wolpert, 2009; Wong et al., 2009), which would mean for a multidirectional tracking task, that stiffness needs to be increased in all directions and the whole limb needs to be stiffened, making it an energetically inefficient strategy. On the other hand, the use of an unpredictable target trajectory in the present study may have limited the options for changing the strategies of corrective movements, and forced subjects in a stabilizing strategy that was energetically less efficient.

Precision demands can be seen as a physical demand but also as a mental demand of the task (Visser et al., 2004). With increased mental demands, a more general increase of motor excitability may be expected, which would also lead to increased muscle activity on the contralateral side of the body. In order to be able to distinguish between a more functional increase of stiffness and a more general increase of muscle activity, muscle activity was measured on both sides of the body. We found that muscle activity in the ECR and FCR in the nondominant and nonactive side of the body was also significantly increased with higher precision demands, although effect sizes were smaller than in the dominant side, showing a medium effect. The simultaneous activation of muscles on the contralateral side, which has no functional reason, may be the result of contralateral motor irradiation (Ridderikhoff, Daffertshofer, Peper, & Beek, 2005). Contralateral irradiation of activation appears to be a graded phenomenon, related to the degree of target muscle activation (Zijdewind & Kernell, 2001). This finding may suggest that motor unit excitation increases with higher precision demands in a rather unspecific way and implies that some caution is merited in interpreting the increase in muscle activity from a functional perspective. However, a general increased motor excitability with increased precision demands seems not likely, because muscle activity in the left and right trapezius muscle was not affected by precision demands. We could have expected trapezius muscle activity in this study to be significantly increased with precision demands. Because trapezius muscle activity was found highly responsive to increases in mental demands (Waersted, Eken, & Westgaard, 1996; Westgaard, Bonato, & Westad, 2006) and subjects perceived tracking a small target as significantly more mentally demanding than tracking a large target in the present study.

In the present study, subjects performed four practice trials, because this had been found to be enough to eliminate learning effects, and to get highly reliable performance outcomes (i.e.,%TT, MDT, and SDDT; Huysmans et al., 2007). Nevertheless, the fact that tracking performance and kinematics were affected by trial indicates that learning continued during the experimental trials, although the effect sizes could be considered small (i.e., in general around .02). The changes in performance with multiple trials pointed at a relative lowering of the demands with practice. Most of the effects found in the kinematics as well as in perceived exertion were in line with this (i.e., changes were opposite to those found with a smaller target size), which thus provides additional evidence of the adaptation of tracking kinematics to changes in (relative) precision demands. In contrast to previous studies (Osu et al., 2002; Thoroughman & Shadmehr, 1999), muscle activity did not decrease over trials. Interestingly, most subjects had not recognized that they had tracked the same target trajectory for four times. This was most likely due to the fact that the target trajectory was rather long and complex and thus unpredictable for the subject and to the fact that only the instantaneous target position was visible on the screen. Even though it seems unlikely that the improvement in tracking performance in the second trial could be completely explained by target memorization, it cannot be excluded that the improvement in performance was partly due to target memorization.

The effects of precision demands on submovement organization found in the present study with a 2D multijoint tracking task are largely in line with the outcomes of the single joint tracking task by Selen, van Dieen, et al. (2006). In response to higher precision demands, subjects made submovements with higher SP gain, resulting in higher movement accuracy. At the same time they trailed more behind the center of target. This seems to reflect a feedback mechanism for error correction. In addition, with higher precision demands, pen pressure was higher and indications of higher cocontraction in the forearm were found. Whether this was due to a higher need for endpoint stability or the result of faster corrective movements was not clear. In the study of Selen, van Dieen, et al. (2006), the higher stiffness and damping with a smaller target was most likely due to an increase of cocontraction and possibly to some extent due to increased reflex gains, while the strategy of increasing mechanical stability in the endpoint through increased friction with the substrate was not available.

In conclusion, higher precision demands led to a different organization of submovements and to increased pen pressure and muscle activity in the forearm extensors and flexors in a 2D tracking task performed with a pen on a digitizer tablet, as was hypothesized. With a smaller target, subjects trailed more behind the center of target and used corrective movements with larger speed pulses of shorter duration, resulting in higher tracking accuracy (i.e., a smaller distance between cursor and the center of the target). This strategy was accompanied by higher muscle activity in the forearm extensors and flexors, presumably to increase endpoint stability.

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