Effects of concurrent physical and cognitive demands on arm movement kinematics in a repetitive upper-extremity precision task

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\textbf{A B S T R A C T}

The effect of concurrent physical and cognitive demands on arm motor control is poorly understood. This exploratory study compared movement kinematics in a repetitive high-precision pipetting task with and without additional concurrent cognitive demands in the form of instructions necessary to locate the correct target tube. Thirty-five healthy female subjects performed a standardized pipetting task, transferring liquid repeatedly from one pick-up tube to different target tubes. In the reference condition, lights indicated the target tube in each movement cycle, while the target tube had to be deciphered from a row and column number on a computer screen in the condition with additional cognitive demands. Kinematics of the dominant arm was assessed using the central tendency and variability of the pipette-tip end-point trajectory and joint kinematics properties of the shoulder and elbow. Movements slowed down (lower velocities and higher area under the movement curves) and trajectory variability increased in the condition with additional cognitive demands, but there were no changes in the kinematics properties such as joint range of motion, times of acceleration and deceleration (as indicated by the time to peak velocity), average angles, or phase relationships between angle and angular velocity of shoulder or elbow movements between the two conditions. Further, there were also no differences in the size or structure of variability of the shoulder and elbow movements.
elbow joint angles, suggesting that subjects could maintain the motor repertoire unaltered in the presence of these specific additional cognitive demands. Further studies should address motor control at other levels of concurrent cognitive demands, and with motor tasks that are less automated than the pipetting task used in the present study, so as to gain an increased understanding of the effect of concurrent cognitive demands for other activities of relevance to daily life.

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1. Introduction

Motor tasks in our day-to-day lives often present a mix of physical and cognitive demands. Motor performance during tasks involving concurrent cognitive and physical demands have so far mainly been explored for automated movements, such as in gait and posture control. In this case, motor execution has generally been suggested to be facilitated by concurrent cognitive tasks with low difficulty, but impeded when the difficulty of cognitive tasks further increases. The relationship between cognitive task difficulty and motor performance in automated movements thus appears to follow an inverted U-shape (Vuillerme, Nougier, & Teasdale, 2000; Riley, Baker, & Schmit, 2003; Deviterne, Gauchard, Jamet, Vancon, & Perrin, 2005; Huxhold, Li, Schmiedek, & Lindenberger, 2006). The explanation for this has been suggested to be that a less difficult cognitive task may promote an external focus of attention, thus allowing the motor system to self-organize and achieve smooth executions of the automated movements, in accordance with the constrained-action hypothesis (Wulf, McNevin, & Shea, 2001; Wulf, Shea, & Park, 2001). On the other hand, when the cognitive task difficulty increases to a point where there is cross-domain resource competition, then motor performance begins to deteriorate (Geurts, Mulder, Nienhuis, & Rijken, 1991; Lindenberger, Marsiske, & Baltes, 2000; Schäfer, Huxhold, & Lindenberger, 2006).

Cognitive tasks commonly used in these experiments have included reaction time tasks, short-term memory tasks involving recalling of digits, rotary auditory stimulation, and n-back digit and spatial working memory tasks. Motor performance has been investigated using metrics such as body centre of pressure displacements and stride characteristics (Vuillerme et al., 2000; Riley et al., 2003; Deviterne et al., 2005; Huxhold et al., 2006; Lövdén, Schaefer, Pohlmeyer, & Lindenberger, 2008). These studies have reached mixed conclusions about whether a concurrent cognitive task affects motor performance, and in what way (see for example, (Lövdén et al., 2008) for a discussion on this topic and (Riby, Perfect, & Stollery, 2004) for a review).

In upper-extremity movements which generally require higher levels of precision and goal-directedness when compared to gait/posture control, the motor task in itself may be more attention-demanding, and thus more ‘controlled’ that gait and posture (Shiffrin & Schneider, 1977). However, for subjects highly proficient in performing the goal-directed movement task, it may tend to be more ‘automated’ than ‘controlled’ (Logan, 1985). So whether superimposed cognitive demands would, for goal-directed upper-extremity tasks, facilitate or impede motor performance is an open question; and it is difficult to form an explicit hypothesis based on previous studies as to the effects of concurrent cognitive demands on arm movement kinematics. So far, concurrent cognitive and motor tasks involving arm movements have been studied mainly in tracking tasks and driving simulators, where the cognitive loads were designed to interfere with the motor task by using distracting visual stimuli intended to divide attention and cause competition of visual and attentional resources (e.g., Ponds, Brouwer, & van Wolffelaar, 1988; Brouwer, Waterink, Van Wolffelaar, & Rothengatter, 1991; Wild-Wall, Hahn, & Falkenstein, 2011). So although motor performance was found to deteriorate in these studies, as measured by time-on-target and metrics describing deviations from target, their relevance to other practical situations in which the cognitive element is an integral and necessary part of performing the task is not clear.
In this context, we designed the present explorative study to investigate the changes in arm movement kinematics that follow from superimposing an additional cognitive demand "on top" of a repetitive upper-extremity precision movement, in the form of a complex instruction on how to perform the repetitive task correctly. Motor control was evaluated by analyzing both the central tendency and variability of kinematics properties of arm movements. Variability was addressed because it is suggested by current motor control theory to have a functional role in skill acquisition (Stergiou, Harbourne, & Cavanaugh, 2006; Bartlett, Wheat, & Robins, 2007; Herzfeld & Shadmehr, 2014; Wu, Miyamoto, Gonzalez Castro, Olveczky, & Smith, 2014), and in preserving performance in the face of unexpected perturbations or fatigue (e.g., Dingwell, Cusumano, Cavanagh, & Sternad, 2001; Riley & Turvey, 2002; Cote, Raymond, Mathieu, Feldman, & Levin, 2005: Madeleine, 2010; Srinivasan & Mathiassen, 2012). Thus, in addition to central tendency metrics, variability metrics have been suggested to reveal important aspects of motor control (Newell & Corcos, 1993), as well as the involvement of top-down cognitive processing (Hausdorff, Yogev, Springer, Simon, & Giladi, 2005; Lövdén et al., 2008). Both the size and structure of movement variability have been suggested to convey important and complementary information, since the former quantifies simple cycle-to-cycle dispersions of kinematics properties while the latter is useful to describe the dynamics of the movement system using non-linear tools (Slifkin & Newell, 1999; Sosnoff, Valantine, & Newell, 2006; Stergiou et al., 2006).

In summary, this study aimed at determining the extent to which additional concurrent cognitive demands necessary for correct task performance change kinematics properties during repetitive arm movements, compared to performing the same movements without these additional cognitive demands.

2. Methods

2.1. Participants and experimental setup

Repetitive arm movements to targets requiring high end-point precision were studied using a "pipetting" task paradigm. Thirty-five right-handed female participants aged 25 (SD 5.8) years and free from any shoulder pain or injury performed the pipetting task in the laboratory. All participants were experienced in pipetting, to avoid any learning effects in motor behaviors. The participants signed an informed consent prior to inclusion. The experiment was approved by the Ethical Review Board in Uppsala, Sweden and conducted in accordance with The Helsinki Declaration. The present experiment was part of a larger study, from which other results have been reported elsewhere (Srinivasan, Samani, Mathiassen, & Madeleine, 2015a; Srinivasan, Mathiassen, Samani, & Madeleine, 2015b).

The task setup is described in detail in a recent publication investigating the effect of work pace on arm movements (Srinivasan, Samani et al., 2015a). Briefly, the participants sat in a rigid chair, with their torsos were strapped to the back of the chair, to restrain any trunk movements. A height-adjustable table surface was positioned to be at each participant’s elbow height when sitting in an upright position. One pipetting cycle consisted of aspirating water from a pickup-tube of diameter 20 mm which was placed to the right and in front of the participant, transferring the water to one of eight small target tubes placed in a 10 × 10 array of identical tubes of diameter 6 mm, and returning to the pickup-tube. One pipetting session consisted of transferring water repeatedly from the pickup-tube to each of eight target tubes 20 times, i.e., in total 160 movement cycles (8 tubes × 20 repeats), in a randomized order (Fig. 1). The speed of performing the task was set at 2.8 s/cycle. The task sequencing and pacing were controlled by a computer program (see below).

The manner in which the sequence of target tubes was indicated to the participants differed between the experimental conditions. In the reference condition (denoted "Phy", Fig. 1), the target tube was indicated by a light mounted below the tube. The timing and sequencing of these lights were controlled by a custom-made computer program. In the condition with additional cognitive demands ("Phy + Cog", Fig. 1), the subjects instead received, on a computer screen in front of them, a ‘tube number’ comprised of a row and a column label indicating which tube to transfer liquid to. The timing and
sequencing of the tube numbers were controlled by the same software program that controlled the lights in the reference condition.

Each pipetting session of 160 cycles lasted 7–8 min, and the order of the Phy and Phy + Cog conditions was randomized, with 10 min of rest in between each session. In order to get familiarized with the setup, all participants performed practice sessions of 100 pipetting movement cycles in both the Phy and Phy + Cog conditions before any actual data collection.

2.2. Data collection and processing

Kinematics data were recorded and processed as described previously (Srinivasan, Samani et al., 2015a). Briefly, data were recorded by means of two synchronized electromagnetic tracking systems (Fastrak, Polhemus, USA), at a sampling rate of 30 Hz, and filtered using a fourth order low-pass Butterworth filter with a cutoff frequency of 3 Hz. A three-segment rigid-body model of the upper arm, forearm and hand segments (described in Domkin, Laczko, Djupsjobacka, Jaric, & Latash, 2005) was used for estimating the shoulder, elbow and wrist joint angles as defined by the ISB conventions (Wu et al., 2005). Thumb forces exerted on the pipette were recorded using a thin-film finger-tip force sensor (A201, Tekscan Inc, USA) mounted on the pipette’s push button, and the force signals were used to identify the time at which each pipetting cycle ended. The kinematics data were sampled continuously for each pipetting session, and then broken down into cycle-to-cycle data based on the pipette-tip velocity and thumb force signals. For each cycle, start and end points were described to extract the ‘transfer’ part of the cycle, i.e., the movement between the pickup tube and target. The start point was defined as the time instant when the pipette tip was at the pickup-tube with minimum velocity; and the end point was defined as the instant when the force on the pipette’s push button was at its maximum (to dispel liquid into the target tube). The time instants when the velocity of the pipette-tip increased above and decreased below 5% of peak velocity were used as cut-off points to further trim each cycle. Cycles of pipette-tip kinematics, shoulder elevation (i.e., conical angle between the upper arm and axis of gravity) and elbow flexion (i.e., the angle between the upper arm and forearm segments) associated with pipetting movements to each target were used for further analysis of kinematics.
2.3. Data analysis

2.3.1. Performance metrics

The following variables were computed for each cycle using the pipette-tip kinematics, the pipette-tip representing the end-point of the kinematic chain:

1. Movement time: the time taken to pick up liquid from the pickup tube and transfer it into the designated target tube, was computed as a measure of temporal performance. Both average movement times and standard deviation of movement times across cycles was calculated.

2. Distance-to-target at the time of peak velocity was determined as the pipette-tip position at peak velocity, in percent of the total distance of the movement from the pickup tube to the target. Both the average and the cycle-to-cycle standard deviation across cycles of this variable were calculated.

3. Trajectory variability (variable error) of the pipette-tip at peak velocity was estimated as the volume of the confidence ellipsoid of the trajectory positions of all cycles (Adamovich et al., 2001).

4. Task performance was quantified by counting the total number of mistakes made by each participant in each complete pipetting session, a mistake being defined as a missed tube or liquid being pipetted to the wrong tube.

2.3.2. Means of kinematics properties

The following variables were computed for each movement cycle to describe the kinematic properties of shoulder elevation and elbow flexion movements (Srinivasan, Rudolfsson, & Mathiassen, 2015c): (1) Range of motion (ROM); (2) peak velocity (Peak Vel); (3) average velocity (Avg Vel); (4) time to peak velocity (Time PV); (5) area under the movement curve (Area); (6) average angle (Avg Ang); and (7) average phase (Avg Ph), where “phase” was used to quantify the relationship between joint angle and angular velocity, and computed as per (Hamill, van Emmerik, Heiderscheit, & Li, 1999).

The overall means of these parameters across all movement cycles for each subject in each pipetting condition was used to describe the central tendencies of the kinematics properties of shoulder elevation and elbow flexion.

2.3.3. Size of cycle-to-cycle kinematics variability

The cycle-to-cycle standard deviations of the seven variables described above were used to describe the size of motor variability in shoulder elevation and elbow flexion movements (Madeleine, Mathiassen, & Arendt-Nielsen, 2008; Madeleine, Voigt, & Mathiassen, 2008). For the first five variables (ROM, Peak Vel, Avg Vel, Time PV and Area), the cycle-to-cycle standard deviation of each variable was first computed across the 20 repetitions to each target, and the median value across all 8 targets was used as an estimate of the cycle-to-cycle standard deviation of that variable for each subject, i.e., ‘ROMSD’, ‘Peak VelSD’, ‘Avg VelSD’, ‘Time PVSD’, and ‘AreaSD’.

For the angle and phase variables, time normalized angles were calculated by expressing the angle recordings in terms of equidistant samples such that each normalized data point represented ~10% of total movement time (cf. Chau, Young, & Redekop, 2005). The standard deviation across all cycles of time-normalized angle was then calculated for each target, and the median of values across all 8 targets was computed as ‘Time norm AngleSD’. Similar calculations were also performed for phase variability to compute ‘Time norm PhaseSD’.

2.3.4. Structure of kinematics variability

Structural variability was quantified using sample entropy and recurrence map analysis. Both methods of computing the structure of motor variability have been used in previous studies of motor control properties (e.g., Madeleine & Madsen, 2009; Samani, Srinivasan, Mathiassen, & Madeleine, 2015). All pipetting cycles to each target were divided into 3 sets with approximately equal number of cycles concatenated together in each set. The sets were offset-corrected by subtracting their mean value, and normalized to their own standard deviation. Sample entropy (SaEn) (Richman & Moorman, 2000), percentage of determinism in the recurrence map (DET) and Shannon entropy of the sequential recurrent map (RMen) (Webber & Zbilut, 1994; Webber & Zbilut, 2005) were calculated, first to each target in each set, and then averaged across the sets. Median values of the indices across all 8 targets
were computed and used as metrics reflecting the structure of motor variability in shoulder elevation and elbow flexion movements. The authors refer to (Samani et al., 2015) for further details concerning the nonlinear analyses.

2.4. Statistical analysis

Since many of the dependent variables were not normally distributed, we used non parametric tests for all comparisons. Wilcoxon signed-rank tests were run on movement time, movement time variability, distance-to-target of pipette-tip at peak velocity, variability of distance-to-target at peak velocity, trajectory variability of pipette-tip at peak velocity, and task performance, to test for the effect of additional cognitive demands on these variables ($p$-values less than .05 were considered statistically significant).

For the shoulder and elbow kinematics properties, since the different variables showed low to moderate pairwise correlations, we compared the experimental conditions using multivariate spatial signed-rank tests, separately for shoulder elevation and elbow flexion means and variabilities (Möttönen & Oja, 1995; Oja & Randles, 2004; Möttönen, Oja, & Serfling, 2005). If the result of the multivariate rank test was statistically significant, post-hoc analysis was then performed for each variable using univariate Wilcoxon signed-rank tests, with Holm’s sequentially rejective procedure to adjust for multiple tests (Holm, 1979). Holm’s adjustment implies that the level of significance is adjusted to $\alpha/n$, where $\alpha$ is set at .05, and $n$ is the rank of the particular univariate test among all univariate tests according to its $p$ value in descending order.

3. Results

3.1. Task performance metrics

Average movement time, expressed as median value across all subjects (inter-quartile range), was higher in the Phy + Cog condition (1.25 (0.24) seconds) than in the Phy condition (1.17 (0.21) seconds; $p < .001$). The cycle-to-cycle standard deviation of movement time was also higher in the Phy + Cog condition (0.28 (0.11)) than in the Phy condition (0.24 (0.08); $p < .001$). Average distance-to-target of the pipette-tip at peak velocity was 56.3% (3.9%) in the Phy + Cog condition and 55.8% (3.9%) in the Phy condition. The cycle-to-cycle standard deviation in distance-to-target of the pipette-tip at peak velocity was higher in the Phy + Cog condition (9.5% (3.9%)) than in the Phy condition (8.8% (2.9%); $p = .04$). The variability of the pipette-tip’s trajectory in 3D was also higher in the Phy + Cog condition (13.4 (7.0) cm$^3$) than in the Phy (13.0 (6.6) cm$^3$; $p = .03$). The number of mistakes made by any particular participant when performing the 160 operations in a pipetting session was higher in the Phy + Cog condition (2 (5.5)) than in the Phy condition (0 (1); $p = .003$).

3.2. Shoulder and elbow joint movement kinematics

The central tendencies of kinematics variables describing shoulder elevation and elbow flexion are shown in Fig. 2(a) and (b) respectively. The multivariate signed-rank test showed that the difference in shoulder joint angles between the Phy + Cog and Phy conditions was significant ($p = .008$). Fig. 2 shows that in the Phy + Cog condition, peak velocity and average velocity decreased by about 10%, and the area under movement curve increased by 10% compared to the Phy condition. Subsequent univariate Wilcoxon signed-rank tests indicated that these decreases in peak and average velocities and increase in area under the movement curve were significant ($p = .004, .009$ and .008 respectively). Similarly, for elbow flexion, the multivariate signed-rank test indicated that the difference in elbow flexion kinematics between the Phy + Cog and Phy conditions was significant ($p = .009$). In this case, there was about 5% decrease in peak velocity and 10% increase in area under the movement curve in the Phy + Cog condition compared to Phy condition ($p = .005$ and .008 respectively).
3.3. Shoulder and elbow joint movement variabilities

Box plots of all motor variability metrics in the two conditions are shown in Fig. 3a (shoulder) and b (elbow). The multivariate signed-rank tests indicated that none of the changes in shoulder or elbow movement variabilities were significantly different between the physical condition and the condition with additional cognitive demands.

4. Discussion

Several studies have been devoted to the effects of concurrent cognitive demands on the motor control of posture and balance (e.g., Huxhold et al., 2006; Deviterne et al., 2005; Riley et al., 2003), but their results cannot simply be extended to the case of repetitive arm movements requiring high precision, as such movements are less automated than standing or walking. To the best of our knowledge, this is the first exploratory study to report detailed kinematics analysis of the central tendency and variability of arm movements in a repetitive task with additional cognitive demands.

The participants in this study performed continuous repetitive pipetting movements from a single pick-up tube to eight different targets which were dispersed among 100 similar tubes in an array (Fig. 1). All participants were experienced in pipetting and were also trained in both experimental conditions before the start of the experiment to ensure that learning effects did not confound the findings of the study. While the Phy condition required subjects to just react to lights identifying the target for
each movement cycle, the cognitive demands in the Phy + Cog condition required subjects to instead decipher instructions from a computer screen. Even though there may be a light cognitive demand in the Phy condition (since the subjects have to identify where the light is, within the tube array, in order to perform the task to the correct target tube), the cognitive demands imposed at the beginning of each movement cycle were considerably larger in the Phy + Cog condition, and had to be integrated with the motor task of reaching to the correct target in order to perform successfully. The additional cognitive demand was designed such that it was still possible to keep up the pace of the task, and perform the task successfully, in almost all cases. We were interested in understanding the extent to which motor control of the shoulder and elbow joints would be affected by this need to integrate motor and cognitive demands in a controlled upper-extremity task.

Motor performance, as quantified by the number of pipetting mistakes made in each condition, was slightly lower in the Phy than in the Phy + Cog condition. Analysis of the pipette-tip trajectory (representing the end-point of the kinematic chain) indicated that the average distance remaining to be covered to target at the time of peak velocity was not different between the Phy and Phy + Cog conditions. However, the size of variability in the distance-to-target at peak velocity was significantly higher in the Phy + Cog condition than in the Phy condition, and similarly, the size of trajectory variability of the pipette-tip in 3D was also higher at the time of peak velocity in the Phy + Cog than in the Phy condition. These changes in trajectory variability (of the end-point of the kinematic chain) are similar to findings from previous studies on tracking tasks (Svendsen, Samani, Mayntzhusen, & Madeleine, 2011) and gait and posture variabilities (Huxhold et al., 2006; Lövdén et al., 2008). However, unlike in postural control, increase in trajectory variability is not necessarily an indicator of worse motor performance in arm movements, as shown by the subjects still being able to execute the task within the required tolerance margin of precision by pipetting into the target tubes at the set pace.
Despite similar motor performance, the mean values of kinematics variables indicated that peak and average velocities and area under the movement curve were significantly changed in the Phy + Cog condition when compared to the Phy condition. Velocities were lower and area under the movement curve was higher, indicating that even though pace was constrained for the total cycle consisting of transfer and return movements from and to the pickup tube, the transfer movements from the pickup tube to the target tubes were slower in the Phy + Cog condition than in the Phy condition. This was also confirmed by the average movement time being larger in the Phy + Cog condition when compared to the Phy condition. However, there were no differences in joint ranges of motion, times of acceleration and deceleration (as indicated by the time to peak velocity), average angles, or phase relationships between angle and angular velocity in the shoulder and elbow joints between the two conditions. There were also no differences in the motor variability of joint kinematics between the two conditions, neither in the size metrics estimated by cycle-to-cycle standard deviations of kinematics properties, nor in the structure metrics based on entropy and recurrence quantification analysis. We observed changes in both the central tendency and variability of kinematics properties in earlier studies of the same pipetting task when task difficulty was increased by higher demands on pace and/or precision (Srinivasan, Samani et al., 2015a; Srinivasan, Mathiassen et al., 2015b). Hence, the present findings of very small, if any, changes with increased cognitive demands were quite surprising, and even unexpected based on previous literature showing that an increase in the overall difficulty of a task can lead to changes in kinematics (Jaric, Russell, Collins, & Marwaha, 2005; Hong & Newell, 2008; Svendsen et al., 2011).

However, the superimposed additional cognitive demands were not intended to make the motor task too difficult as we wanted the subjects to still be able to perform the paced repetitive motor task. It is thus conceivable that the Phy + Cog and Phy conditions were too similar to result in tangible variability changes. Côté (2014) suggested that motor variability is a property that reflects leeway and margin of maneuver, to describe the general motor repertoire. One can then extrapolate that the tested conditions, while being relevant to everyday situations, were not challenging enough to induce changes in the elbow and shoulder kinematics variabilities in healthy participants.

Previous studies of posture and gait control have proposed that an “easy” cognitive task may improve motor performance, while a further increase in cognitive demands would worsen performance in an inverted U-shaped relationship (Huxhold et al., 2006). However, we did not find any change in performance or movement variability with the level of cognitive difficulty introduced in repetitive pipetting, and we think that any further increases in concurrent cognitive demands might only worsen motor performance in this task. This suggests that there may not be any inverted U-shaped relationship between cognitive task difficulty and motor performance in arm movements as claimed for gait and posture control, possibly because arm movements are not automated enough to benefit from the ‘external’ focus of attention (Wulf, Shea et al., 2001). Further studies focusing on systematically manipulating the difficulty of cognitive demands during goal directed movements of the arms are warranted to examine this hypothesis. Further studies should also address motor tasks that are less automated than the short-cycle, easy task used in the present study, so as to gain an increased understanding of the effect of concurrent cognitive demands under further conditions of relevance to daily activities, such as in the learning phase of a novel motor task, or when performing a motor task that requires frequent adjustments due to unpredictable perturbations of the task or the setting in which it is performed.

In conclusion, increasing the cognitive demands required for successful performance in the present short-cycle repetitive manual task did not lead to any notable changes in joint kinematics variabilities of the shoulder or elbow joints, even though the movement slowed down and the variability of the pipette-tip end point trajectory increased. Thus, the present exploratory study suggests that the motor repertoire in the repetitive arm movement was maintained unaltered in healthy participants regardless of the additional concurrent cognitive demands.

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