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Interaction between force production and cognitive performance in humans

Inge Zijdewind, Hiske van Duinen, Ronald Zielman, Monicque Lorist

Abstract

A dual-task paradigm was used to examine the effects of the generation of force on cognitive performance. Subjects (n=22) were asked to respond to auditory stimuli with their left middle or index finger and concurrently maintain a sub-maximal contraction with their right index finger at one of two different force levels. The contraction was maintained for approximately 12 seconds and the target force level was alternated between 30% and 60% of the maximal force. Force production was the primary task of interest; performance of the (secondary) choice reaction time task (reaction times and accuracy) was used as an index of the amount of interference between the two tasks. All subjects were capable of performing the force tasks adequately. Significant interference was observed between the level of force production and cognitive performance. At the higher force level, subjects performed the cognitive task more slowly and less accurately compared to the lower force level. Our results show that the execution of high-effort motor behaviour interacts with cognitive task performance. However, comparison with the data obtained during fatiguing contractions in a previous study (Lorist et al., 2002) showed that the interference was stronger during fatiguing contractions than during the present high-effort motor behaviour. The results suggest that force-related factors can explain part of the fatigue-related interference between force production and cognitive performance. This result could have consequences for interpreting cognitive deficits observed in patients suffering from motor dysfunction.

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Introduction

In everyday life, people often perform motor tasks in combination with cognitive tasks without a decrement in the performance of either task. For instance, one is perfectly capable of discussing everyday problems while carrying a shopping bag without any obvious interference. However, in a previous study (Lorist et al., 2002), we have shown that progressively more interference can emerge when performing a fatiguing motor task in combination with a cognitive task. In that study, subjects produced a fatiguing contraction with their right index finger while simultaneously performing a choice reaction task with their left hand. The data showed that – while force maintenance became increasingly difficult due to fatigue – the reaction times progressively increased and response accuracy decreased. Thus, motor fatigue resulted in deterioration of cognitive task performance. We attributed the decline in performance to increasing demands on central resources caused by the fatiguing motor task, thus limiting the remaining available capacity for the performance of the secondary cognitive task.

It is known that prolonged contractions induce changes on both peripheral (Bigland-Ritchie et al., 1978; Bigland-Ritchie et al., 1986a,b) and central levels (Gandevia, 2001). In addition, changes on peripheral levels often necessitate changes on central levels. For instance, maintaining a sub-maximal contraction requires a progressively increasing supraspinal drive to the target motoneurones to compensate for the decline in muscle fibre force (Bigland-Ritchie et al., 1986a,b; Zijdewind et al., 1995). Therefore, the decline in cognitive performance observed in our previous experiments (Lorist et al., 2002) could be due to the fact that at the end of the fatigue test subjects have to produce a higher supraspinal drive to the relevant motoneurone pool due to fatigue-induced changes in the periphery (e.g., excitation contraction coupling). However, fatigue-related changes in central mechanisms driving motor behaviour (e.g., cortical excitability changes) may also be of importance. Several studies have demonstrated fatigue-related changes in excitability of the motor cortex or levels upstream of the motor cortex (see for review, Gandevia, 2001; Taylor and Gandevia, 2001). It seems reasonable to assume that because of the fatigue-induced changes in the excitability of (pre-) motor areas, force production places stronger demands on the attentional system and thereby induces a decline in the attentional capacity remaining available for a concurrently performed (cognitive) task.

To gain more insight in the effect of motor fatigue on the relationship between motor- and cognitive performance we need to manipulate one of the two important parameters: the central drive to the motoneurones (as a result of peripheral fatigue) or
the fatigue-induced changes in central mechanisms driving motor behaviour (central fatigue). It is difficult to induce central fatigue without changing the central drive to the motoneurone pool, but it is possible to change the central drive to the motoneurone pool without inducing fatigue, namely by manipulating the desired level of the contraction force. Therefore, we asked subjects to perform a cognitive reaction task with a concomitant motor task, using two target force levels (alternating between 30% and 60% of maximal contraction). The parameters of the cognitive task (i.e. reaction times and accuracy) served as an indication of the strength of the interference between the two tasks. If an increase in supraspinal drive is an important determinant of the interference between motor and cognitive performance, we would expect to find an increase in reaction times and/or decrease in accuracy in the 60% force condition compared to the 30% force condition.

Methods

Participants

Twenty-two healthy adults (mean age: 22.6 ± 2.0 years, 10 females, 12 males) participated in the study. All subjects were right-handed and had (corrected to) normal vision and intact hearing. Informed consent to participate was signed prior to the study. All procedures were undertaken with the approval of the local ethics committee and conformed to the standards set out in the Declaration of Helsinki.

Experimental set-up

The experimental set-up was the same as described previously (Lorist et al., 2002). Subjects sat at an experimental table with their forearms resting on the table. The abduction force of the index finger of the right hand was measured. To enable accurate force measurements, the right forearm and hand were immobilised in a position halfway between pronation and supination using pressure plates and Velcro tape. The right index finger was held slightly abducted within a snugly fitting ring around the proximal interphalangeal joint; this ring was rigidly connected to an isometric force transducer (for details see Zijdewind and Kernell, 1994).

Electromyographic recordings (EMG) were made of the first dorsal interosseus muscle (FDI) of the right hand. A 4-mm Ag-AgCl electrode (in-vivo metrics, Healdsburg, Ca, USA) was placed over the belly of the FDI and a second electrode was attached to the first metacarpal phalangeal joint. A band-shaped electrode around the wrist served as a ground electrode. The EMG and force recordings were amplified, filtered (EMG: 10Hz-
1kHz, force: DC-500 Hz) sampled (2000 Hz and 500 Hz, respectively), and analysed using a PC equipped with a data-acquisition interface (1401+ and Spike-2 software, Cambridge Electronic Design, Cambridge, UK).

**Tasks**

The experiment consisted of 3 tasks: 1) a cognitive task, 2) a motor task and 3) a combination of the two tasks; the dual task.

The **cognitive task** consisted of an auditory choice reaction time task (CRT). The stimuli, 500 or 900 Hz pure tones were presented binaurally via speakers (duration: 50 ms, intensity: 70 dB). The inter-tone interval varied randomly between 1100 and 1300 ms. The probability of the presentation of the tones was unequal; one tone had a probability of 70% (frequent tone) while the other tone had a probability of 30% (infrequent tone).

Random sequences of frequent and infrequent stimuli were presented in series of 8 stimuli (a period of approximately 10 seconds), followed by 30 seconds rest. Subjects were asked to respond to the auditory stimulus by pressing one of two response-buttons with either their middle or index finger of the left hand and encouraged to perform the task as fast and as accurately as possible. Half of the subjects were instructed to respond with their middle finger to frequent stimuli and with their index finger to infrequent stimuli. The other half of the subjects received opposite instructions. For half of the subjects in each group, 500 Hz tones were the frequent stimuli, while for the other half of the subjects these tones served as infrequent stimuli. As a result, there were four different versions of the choice reaction task (CRT): 1) frequent stimuli 500 Hz, middle finger response and infrequent stimuli 900 Hz, index finger response; 2) frequent stimuli 900 Hz, middle finger response and infrequent stimuli 500 Hz, index finger response; 3) frequent stimuli 500 Hz, index finger response and infrequent stimuli 900 Hz, middle finger response; and 4) frequent stimuli 900 Hz, index finger response and infrequent stimuli 500 Hz, middle finger response. The presentation of stimuli and the collection of the subjects’ responses were controlled by Micro Experimental Laboratory Professional Software (MEL v2.0; Schneider, 1988), in conjunction with the MEL Serial Response Box.

The **motor task** consisted of index finger abductions of the right hand. All subjects performed three maximal voluntary contractions (MVCs); the largest MVC was used as control value (cMVC). Subjects had to start the MVC after a 2000 Hz tone; they ended the contraction 4 seconds later after a 200 Hz tone.
In the dual-task condition the CRT was combined with sub-maximal contractions. Subjects had to produce contractions at 30% or 60% cMVC for approximately 12 seconds (after a 200 Hz tone). Two seconds after the start of the contraction, subjects had to respond to the stimuli (500 and 900 Hz) with their left hand while they maintained the sub-maximal contraction with their right index finger. Series of 8 CRT stimuli (8.9 – 10.3 sec, depending on the inter-stimulus interval) were presented during the contraction (12 s). To facilitate the response of the subjects, all series of stimuli started with a frequent stimulus (this stimulus was not used for further analysis).

A dual-beam oscilloscope continuously showed the produced and the desired force level of the subjects (30% or 60% cMVC). A second 200 Hz tone indicated the end of the sub-maximal contraction; this was followed by 30 s of rest. During the dual task the maintenance of the sub-maximal force was the primary task, while responding as quickly and accurately as possible to the auditory stimuli was the secondary task. To balance out the effects of practice and fatigue, blocks of 30% cMVC and 60% cMVC were alternated for a total of 40 blocks (20 blocks each). After every 10 blocks, subjects had to perform an MVC.

**General procedure**

The experiment lasted approximately one hour and consisted of four segments which were presented in the following order (Fig. 1):

1) **Practice**: one group of 100 choice reaction time stimuli (CRT), followed by ten blocks of 8 CRT trials with an MVC performed after every fifth block;
2) **Force measurements**: determination of ‘control MVC’ (cMVC).
3) **Cognitive task**: ten blocks of 8 CRT stimuli. An MVC was performed at the start of the task and after every fifth block.
4) **Dual task**: subjects had to maintain a contraction at a level of 30% or 60% cMVC with their right index finger followed by 30-s rest; during these contractions blocks of 8 CRT stimuli were presented. In total 40 contractions had to be produced, and after every tenth block an MVC.

**Data analysis and statistical procedure**

Each block of stimuli started with a frequent stimulus. As the subject knew which initial stimulus was presented this stimulus was excluded from statistical analysis. As suggested by Wilcox and Keselman (2003) we calculated 20% trimmed mean reaction times. This means that when the data are put in ascending order, both the largest 20%
and the smallest 20%, are excluded. Trimmed mean values are preferable because they are less influenced by outliers compared to mean values and still maintain a high power under normality (in contrast to the median). The trimmed mean was calculated for reaction times of the correct responses for every 5 blocks of stimuli. Thus for the single cognitive task (10 blocks) 2 mean values were determined. For the dual task (20 blocks at 30% cMVC and 60% cMVC) 4 values were determined for the 30% cMVC and 4 values for 60% cMVC level (period-1, period-2, period-3 and period-4). Accuracy was determined by dividing the number of correct responses by the number of presented stimuli.

![Diagram](image)

**Figure 1.** General experimental protocol. After a practice session (not shown in this schematic drawing) subjects had to produce three maximal voluntary contractions to determine their maximal voluntary force(cMVC). The single task condition consisted of a choice reaction time (CRT) task with a maximal force contraction (MVC) after 5 series of CRTs. During the CRT a set of 8 stimuli, both frequent (70% occurrence) and infrequent stimuli (30% occurrence) were presented in each serie. Subjects had to respond to the 8 stimuli with either their *left* middle or index finger. In the dual-task condition the subject had to produce a 30% or 60%MVC with their *right* index finger concomitant with a CRT with the *left* hand. Every 10 blocks (5 blocks at 30% and 5 blocks at 60% MVC) were followed by an MVC. In total subjects had to perform 40 blocks of the dual task.
Trimmed mean reaction times and mean accuracy percentages were calculated for each subject separately for frequent and infrequent stimuli. Kolmogorov-Smirnov tests showed that the reaction times did not differ significantly from a normal distribution; therefore, repeated-measures ANOVAs were used to determine significant differences for the reaction time data. For the single task, we used a 2 x 2 factorial design with the within-subject factors: stimulus (frequent and infrequent) and time-on-task (period-1 and period-2). For the dual task, we used a three-way ANOVA with a 2 x 2 x 4 design with the within-subjects factors: force-level (30% and 60%), stimulus (frequent and infrequent) and time-on-task (period-1, period-2, period-3, and period-4). When the main analysis indicated a significant effect of a factor or an interaction between factors, we performed follow-up analyses, correcting for multiple comparisons according to Bonferroni. The Kolmogorov-Smirnov test showed that the accuracy data were not normally distributed; therefore, we used the non-parametric Friedman analysis to analyse the accuracy data.

Mean force was calculated for every contraction; force-variability (CV) was determined by dividing the standard deviation (SD) by the mean force level. The EMG recordings were rectified and a mean EMG level was calculated for every contraction over the same time period as the force analysis. Like the cognitive parameters, the physiological parameters force, EMG and CV were also averaged for every 5 blocks. Statistical differences in force, EMG and CV were determined by 2 x 4 ANOVA with force level and time-on-task as within-subject factors.

In the text group data are expressed as mean ± SD, in figures as mean ± SE.

Results

Single-task performance

Figure 2 shows the mean data for the reaction times and accuracy measurements for the single task. In this condition (no force production with the right index finger) a two-way repeated ANOVA revealed a significant main effect of frequency ($F_{(1,21)}$=26.44; p<0.001) and time-on-task ($F_{(1,21)}$=5.825; p<0.05) on the reaction times. Frequent stimuli resulted in faster reaction times (289 ± 40 ms) than infrequent stimuli (330 ± 40 ms). For the single task, reaction times declined significantly from the first to the second time-period, probably due to a training effect (period-1: 315 ± 49 ms versus period-2: 305 ± 41 ms). No interaction between frequency and time-on-task was found ($F_{(1,21)}$ =0.133; n.s).
The non-parametric tests for accuracy values also showed a significant effect of frequency (Z=-3.59; p<0.001); subjects responded with significantly higher accuracy to the frequent stimuli (98.0 ± 3.5%) than to the infrequent stimuli (92.0 ± 9.5%). In contrast to the data on reaction times, no significant effect of time-on-task was found for accuracy.

**Dual-task performance**

The dual-task paradigm was designed to study the influence of the execution of different force levels on cognitive task performance. Statistical analysis of the reaction times indeed revealed a significant main effect of force level in the dual task (30% vs. 60% MVC; \(F_{(1,21)}=10.01, p=0.005\)). Also stimulus frequency (\(F_{(1,21)}=79.54, p<0.001\)) and time-on-task (\(F_{(3,63)}=11.74, p<0.001\)) showed significant effects on the reaction times. As in the single task condition, subjects responded faster to frequent than to infrequent stimuli. For the effect of time-on-task, post hoc tests revealed a significant difference between the reaction times in the first (347 ± 55 ms) and the second period (325 ± 40 ms; p<0.05), no significant differences were found between the other consecutive blocks (period-2 vs. period-3 or period-3 vs. period-4; see Fig. 3). We have attributed this decrease in reaction times to a learning process.

No significant interactions between the various factors were found.

For the accuracy values, the non-parametric Friedman analysis showed a significant effect of the frequency of the stimuli \(Z=-7.625; \ P<0.001\). Frequent stimuli resulted in a
more accurate response (97 ± 4%) than the infrequent stimuli (90 ± 13%). Overall, a significant effect of force-level was found on the accuracy (Z= -3.705, p<0.001; 30%: 95 ± 8% versus 60%: 92 ± 13%); subjects responded less accurate at higher force levels. Further analysis showed that for the frequent stimuli no significant effect of force-level was found (Chi-square=10.67, p>0.1); the significant effect of force-level was only due to high accuracy of the infrequent stimuli in the second period of the 30% cMVC condition (p=0.001, Fig. 3D). In addition, a significant effect of time-on-task was found (p<0.05). Detailed analysis showed that the significant effect was due to a significant increase in the accuracy of frequent stimuli in the second time-period (period-1 vs. period-2, p<0.05; period-2 vs. period-3, p<0.05). No other significant differences were observed for frequent and infrequent stimuli (Fig. 3C).

**Figure 3.** Mean reaction times (± SE) and correct responses (% ± SE) during dual-task performance. Reaction times and accuracy are shown separately for frequent (panel A and C) and infrequent stimuli (panel B and D). The dual task consisted of a choice reaction time task combined with a sub-maximal force task at different levels of target force; 30% MVC (interrupted line) and 60% MVC (straight line). Significant differences were observed between two force levels (+), an asterisk (*) denotes a significant difference between two adjacent time-periods. See ‘Results’ for further statistical analysis.
Figure 4 shows the force, EMG and variability (CV) values for the two target force levels (30% and 60% cMVC). As could be expected, a main effect of force-level was found for the parameters force ($F_{(1,21)}=2783.30; \ p<0.001$) and EMG ($F_{(1,21)}=314.79; \ p<0.001$); however, no effect of force was found for the force-variability ($F_{(1,21)}=0.776; \ p>0.3$). No main effect of time-on-task was found for the parameters force and CV. For the EMG-values, however, a significant interaction was found between time-on-task and force-level ($F_{(3,63)}=17.81; \ p<0.001$); post hoc analysis revealed significant differences in the time-course of EMG values during the 30% and 60% force levels for all consecutive time-periods ($p<0.05$ or less for all consecutive time-periods). During the 30% levels, EMG-values showed a small increase ($29.2 \pm 9.5$ to $32.1 \pm 11.1$); while during the 60% levels EMG-values showed a small decline ($62.6 \pm 11.4$ to $57.5 \pm 13.6$; see Fig. 4). The small increase in EMG in the 30% condition was probably due to peripheral fatigue. Peripheral fatigue necessitates an increased drive to the muscle to maintain the target force; thus an increase in EMG without a change in the force production. In the 60% condition, the force tended to decrease slightly which may explain the small decline in the accompanying EMG-values ($58.7 \pm 2.42$ to $57.34 \pm 5.45$).

Figure 5 shows the time-course of the interspersed MVC values during the dual-task condition. Statistical analysis showed a significant decline in the MVC-values with time-on-task (from $91 \pm 6$ to $77 \pm 12 \%$ cMVC; $F_{(2,1,46.8)}=25.51; \ p<0.0001$). Post-hoc analysis showed significant differences for period-1 versus period-2 ($p<0.001$), and period-2 vs. period-3 ($p<0.05$). We have used the MVC-values as a covariate for the reaction time data. However, no significant interaction was observed with reaction times. This result implies that the results of reaction time data were not statistically influenced by the decline in MVC values.
Our data showed a significant interference of isometric force production on cognitive performance. The extent of the interference was dependent on the amount of force that had to be produced; higher force levels resulted in longer reaction times and less accuracy compared to the lower force condition.

In a previous series of experiments we have shown that performance on the same cognitive task in the dual-task paradigm was seriously affected by motor fatigue (Lorist et al., 2002). However, it was uncertain whether the observed deterioration in the choice reaction time task was mainly due to the increasing demands placed on central mechanisms (because of fatigue-related changes) or to the increasing central drive to fatiguing muscle fibres. In other words: is the interference between the motor task and the cognitive task induced by motor fatigue caused by changes on primarily central or primarily peripheral levels (central versus peripheral fatigue).

In the present study we have shown that increasing the target force levels and consequently increasing the drive to motoneurones induced a decline in cognitive task performance. However, the decrease in cognitive performance in our previous study (Lorist et al., 2002) – increase in reaction times and number of errors (see Fig. 6) – was much larger than the changes we have observed in the present experiment; despite the fact that the force levels were comparable. That is, in the previous experiment the (fatiguing) motor task consisted of sustained 30% cMVC contractions. The subjects had to generate this force concurrently with the same cognitive task. At the end of the fatigue test, MVC values had declined approximately to half of their cMVC. This suggests that at the end of the sub-maximal force task (30% cMVC), the subjects were actually producing 60% of their actual MVC. Thus, if the central mechanisms driving the muscle fibres were the major cause of the interaction, one would expect in the present study
about the same amount of interference. However, the amount of interaction in the present study is much smaller. This result indicates that in addition to force-related factors, additional fatigue-related factors are also important for explaining the interference between motor behaviour and cognitive performance during motor fatigue.

The finding that both force- and fatigue-related factors are of importance for the explanation of the interference between force production and cognitive performance is consistent with results of Schubert and colleagues (Schubert et al, 1998). They combined an auditory CRT with either a force task (approximately 50%-MVC) or a displacement task (minimal force requirements). Significantly slower reaction times were found with the concurrent force task compared to the displacement task (Schubert et al, 1998). Yet in neither condition did their results show differential time-on-task effects. Although the force level in their study was 50% MVC, it seems that the demands in their protocol were not high enough to induce fatigue and the related effects on central mechanisms. This is in agreement with the observation that their subjects were still able to perform the force task at the end of their experimental session.

Previous studies that investigated the interference between isometric force and cognitive performance have shown conflicting results. Muscle contractions may have facilitating (Bills, 1927; Bills and Stauffacher, 1937; Moran and Cleary, 1986, 1988; Parker, 1973; Pinneo, 2003) or inhibitory effects on cognitive performance (Bills, 1927; Bills and Stauffacher, 1937; Moran and Cleary, 1986, 1988; Parker, 1973; Pinneo, 2003). An important reason for these conflicting results might be the complexity of the cognitive task: the largest facilitating effects of muscle contractions were found on relatively simple tasks such as simple reaction time task. The facilitating effects of muscle contractions on more complex tasks were smaller or even inhibitory effects were found (Bills, 1927; Bills and Stauffacher, 1937; Moran and Cleary, 1986, 1988; Parker, 1973; Pinneo, 2003). In addition (in accordance with our present data) the level of muscle contraction is of importance. In our study, we have used relatively strong contractions compared to those that induced facilitative effects. If we compared the data in the second period of the single and dual task it is noteworthy that we did not find a significant difference in the reaction times in the single task compared to dual task in the low force condition ($F_{(1,21)}=4.51, p>0.5$). During the high-effort 60% force task, however, we found a decline in cognitive performance. This result underlines the importance of the target force level while studying the interference between the cognitive and motor tasks.
The interference of the motor task with the cognitive task could be due to interaction in different brain areas, a possible candidate in this respect being the dorsolateral prefrontal cortex. This area is involved in a wide range of tasks related to working memory and response selection (Rowe et al., 2000; Rypma and D'Esposito, 1999). Interestingly, increasing activity in this area is also observed during isometric motor contractions at progressively higher force levels (Dettmers et al., 1995).
Our data demonstrate that when performance of a motor task places stronger demands on central attentional mechanisms (during higher force levels or fatigue) the cognitive performance declines. In several patient groups performance of motor tasks is more demanding than for healthy control subjects. The results of this study suggest that this could affect performance at a concurrent task (see for instance Bloem et al, 2001a, 2001b; Geurts and Mulder, 1994). Furthermore, fatigue is a symptom common to many neurological disorders, including multiple sclerosis, postpoliomyelitis, amyotrophic lateral sclerosis, spinal cord injury and chronic fatigue syndrome (see for review e.g. Chaudhuri and Behan, 2004; Thomas and Zijdewind, 2005) and in these patients fatigue may affect cognitive performance even more. It is therefore noteworthy that often these disorders are associated with deficits in cognitive performance (Camp et al, 1999; Michiels and Cluydts, 2001; Pelosi et al, 1997).

In conclusion, our study shows that, when performing a motor task in combination with a choice reaction time task, the level of force production interferes with cognitive task performance. Changes in the central nervous system elicited by motor fatigue seem to have an additional detrimental effect on cognitive task performance. Besides of being of interest for understanding processes associated with motor and cognitive performance, this finding is also important for interpreting cognitive deficits observed in patients suffering from motor dysfunction.