Short-term mobilization of processing resources is revealed in the event-related potential

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Abstract
This study investigates whether an occasional effortful improvement of performance, as asked for by a precue, is reflected in event-related potential (ERP) changes. To estimate the limits of possible effort-induced behavioral and ERP changes, we manipulated the time between precue and imperative stimulus (IS; precue interval, PCI). The subjects could, in fact, improve their performance in the effort trials, with all but the shortest PCI. The postcue ERP revealed a fronto-central contingent negative variation (CNV), which was preceded by a frontal positive/occipital negative wave (P2/N2). Both the P2/N2 and the CNV were larger for effort than for standard trials for all PCIs. For the shortest PCI (300 ms), the CNV increase was seen after the IS. The CNV increase for PCIs 600 and 300 began at about 400 ms postcue. The results suggest that effortful performance improvement is associated with prior increase of a frontocentral CNV and a preceding P2/N2. The CNV increase is thought to reflect the activity of a frontal executive process by which additional processing resources can be mobilized on a trial-to-trial basis within less than 500 ms.

Descriptors: Event-related potentials, Contingent negative variation, Effort, Preparation, Processing resources

Everyday experience tells us that even when we work hard on a task, under some circumstances we are able to enhance our effort. Subjectively, we have the impression that we can, within certain limits, deliberately adjust our level of performance according to internal standards or external demands and, under most circumstances, are able to improve our performance when willing to do so.

The existence of some kind of a “reserve of effort” is suggested by studies that investigate performance under stress, one of the core findings being that humans are, at least for some time, able to maintain a certain level of performance despite adverse influences (cf. Hockey, 1997). However, according to the cognitive-energetic models proposed by Hockey (1997) and Sanders (1983), effort is not a normal condition and invoked only under the influence of stressors (cf. Sanders, 1998, p. 394ff for a further discussion).

Studies related to compensatory effort investment usually cover a time range of at least several minutes, often several hours. We were interested in more short-term, phasic processes of effort investment and their modulatory influence on basic information-processing performance, a topic that is widely neglected in the literature. One reason for this neglect is that, at least in some areas of cognitive psychology, energetical constructs are believed to be unimportant for the analysis of information processing (cf. Hockey et al., 1986). Another assumption that prevails in the information-processing literature is that the capacity of the information-processing system is fixed, resulting in necessary performance decrements in one measure of performance (e.g., accuracy) when another performance measure (e.g., speed) is improved as a result of “trying harder.” Thus, it is believed that when one is trying to respond particularly fast, this is necessarily accomplished by a shift of performance criteria or to fast guessing, resulting in a speed-accuracy trade-off (cf. Sanders, 1998, p. 39ff). Beyond that, even the ability of humans to dynamically adjust response criteria on a trial-to-trial basis is questioned (cf. Strayer & Kramer, 1994).

In a recent study, Kleinsorge (2001, Experiment 2) showed that participants in a choice reaction time experiment were able to dynamically adjust their response speed on a trial-to-trial basis. In the first phase of the experiment, participants practiced the task until a stable baseline performance was reached. After this practice phase, precues were introduced that instructed participants, with a variable precuing interval (PCI), to either respond especially fast, that is, to invest some extra effort, or to respond at baseline level, that is, to invest no extra effort. Successfully responding especially fast in the “effort trials” was rewarded by a monetary bonus, with no possibility of obtaining this bonus by slowing down in the other trials. Participants were able to speed up responding in the effort trials, with the amount of this speed-up being a function of the length of the PCI. Only a
relatively small part of this speed-up could be attributed to a speed–accuracy trade-off, whereas the main part was due to a real improvement of performance.

In the present study, we wanted to investigate electrophysiological correlates of participants’ effort to respond especially fast without making more errors. There are few electrophysiological studies that have investigated effort-related changes in electroencephalography (EEG) and event-related potentials (ERPs). Concerning the EEG, frontal midline theta activity has been frequently associated with effort (e.g., Gevins et al., 1990; Mizuki, Tanaka, Isozaki, Nishijima, & Inanaga, 1980). Concerning ERPs, authors have mainly focused on the P300 complex (e.g., Isreal, Chesney, Wickens, & Donchin, 1980; Ullsperger, Metz, & Gille, 1988) or on slow negative potentials, such as the readiness potential, which precedes movements, or on the more general phenomenon, the contingent negative variation (CNV), which precedes task-relevant stimuli (e.g., Birbaumer, Elbert, Canavan, & Rockstroh, 1990; Brunia, 1988; Rösler, 1991). Freude and colleagues (Freude, Ullsperger, Krüger, & Pietschmann, 1988, 1989; Freude, Ullsperger, & Mölle, 1995) recorded the readiness potential (BP) before a self-paced movement that started the next trial of a cognitive task. They could show that the BP was enhanced when the task was performed under high (vs. low) time pressure or after prolonged workload, or when performance was good (vs. poor). These authors suggested that the BP contains nonmotor activity that is related to the allocation of processing resources to the task-relevant cognitive process, rather than to motor preparation. In fact, we have shown that the late CNV in correct trials is enhanced in subjects with good performance (low error rate), irrespective of reaction time (Hohnsbein, Falkenstein, & Hoormann, 1998). Also, we and others have shown that the CNV is enhanced when time pressure is enhanced between blocks (Falkenstein, Hohnsbein, & Hoormann, 1994a; Wascher, Verleger, Jaskowski, & Waschkekuhn, 1996). Moreover, on fast trials within a block, the CNV was also enhanced compared to slow trials (e.g., Hillyard, 1969). This shows that trial-to-trial shifts in performance that are not externally induced are reflected in the CNV. Hence, it can be hypothesized that also voluntary and effortful control of performance on a trial-by-trial basis, as induced by external cues, might be reflected in CNV changes. To the best of our knowledge, there is no study that has explicitly manipulated effort by external cues on a short-term trial-by-trial basis while observing brain activity. This was the main goal of the present study. A second goal was to assess the limits, that is, the maximum speed of such possible CNV changes.

In sum, in the present study, we ask whether the trial-by-trial voluntary mobilization of extra effort is reflected in changes of the ERP, particularly of the CNV, and whether such possible changes depend on preparation time.

Materials and Methods

Participants, Stimuli, and Task

Eighteen healthy right-handed young people (mean age: 22.5 years; 8 men) participated in the study. The participants were students and were familiar with computers. All participants gave informed consent for their participation in the study.

The participants were seated in front of a computer monitor; the viewing distance was 57 cm. They fixated a dot that was presented continuously in the center of the monitor. Each trial began with the simultaneous appearance of two vertical gray bars (size 0.3° × 0.1° visual angle) at 5° to the right and left of the fixation point (warning stimulus; S1). The bars immediately moved symmetrically toward the fixation point, which took exactly 1.200 ms. During this period, the bars simultaneously changed their color (cue; S2) either to blue (which signaled a standard trial) or to red (which signaled an effort trial). Standard and effort trials were randomized within a block; the probability for standard trials was 0.8 and for effort trials 0.2. At the moment the bars coincided, they disappeared and an imperative stimulus (S3) was presented instead at the fixation point. The imperative stimulus was one out of four letters (A, E, O, U); its duration was 200 ms. The size of the letters was 0.3° × 0.4°. The participants had to respond to each letter by pressing the appropriate one out of four keys with the right or left middle or index finger. The probability of 0.2 for effort trials was chosen first to replicate the design used by Kleinsorge et al., who succeeded in having their subjects invest extra effort. Also effort should be the exceptional state; this would not be the case if the probability of effort trials was about as high as that for the standard trials, for example, 50%.

To assess the maximum speed of possible CNV changes due to effort we manipulated the temporal distance between the informative cue (i.e., the color change) and the imperative stimulus (precue interval, PCI) in four steps: 1,200, 900, 600, and 300 ms. The four PCIs were equiprobable and randomized within a block. These steps were chosen to match those used by Kleinsorge (2001).

The intertrial interval was 2,500 ms. Twelve blocks of 100 trials each were presented in the main test phase. The participants were instructed to respond as fast as possible in the effort trials, but to avoid committing more errors than in the standard trials. The participants received a bonus of 0.5 Euros after each block when their average reaction time (RT) in the effort trials was faster than the fastest average RT in the standard trials of all the preceding blocks, and when they committed not more than two errors (10%) in the effort trials. In a preceding training phase (six blocks of 100 trials) the participants practiced the mapping of the stimuli to the responses; in this phase the bars remained gray, and no extra effort was required.

ERP Measurement and Data Analysis

As behavioral variables reaction time and error rates were measured. The EEG was recorded from 64 electrodes (essentially the 10–10 system; Chatrian, Lettich, & Nelson, 1985) mounted in a cap (ECI Inc.) with Cz as primary reference. In addition, the horizontal EOG was measured between the outer canthi of both eyes, and the vertical EOG was measured from above and below both eyes. The EEG was filtered between 0.01 (two-pole high pass) and 70 Hz (eight-pole low pass; Butterworth) and sampled with 250 Hz. The recording equipment was EPGA amplifiers (Sensorium Inc.), the acquisition software was ACQUIRE (NeuroScan Inc.). The EEG data were processed with the software package “Konstanz Format,” provided by P. Berg. Eye movement artifacts were removed by the method of Berg & Scherg, 1994). From the EEG, stimulus-locked ERPs were computed beginning 200 ms before the onset of the bars and ending 1,200 ms after the onset of the imperative stimulus, hence amounting to 2,600 ms total length. The ERPs were referenced to average reference (i.e., the average voltage across all electrodes). Epochs in which the amplitude exceeded ± 50 µV were discarded. Originally, 300 trials per PCI (240 standard and
60 effort trials) were available. About 10% of all trials had to be discarded because of artifacts; hence about 216/54 trials remained for standard/effort per PCI and participant. The ERP data were filtered digitally with a 17 Hz low pass.

The “P2/N2” was defined as the maximum positive peak over the anterior scalp (which was negative at the posterior scalp) in the window 150 to 350 ms after the cue (S2). Its latency was measured at FCz (its anterior maximum) and analyzed by an analysis of variance (ANOVA) with the factors PCI (1200, 900, 600, 300) and effort (standard, effort). The amplitude of the P2/N2 was measured for a grid of 4 × 5 electrodes centered over the anterior scalp and a grid of 2 × 5 electrodes over the posterior scalp. The anterior grid covered the four rows from antero-frontal to central; in each row 5 electrodes, namely the midline and 2 (inner and outer) right and 2 (inner and outer) left electrodes were included. The four rows included AF7, AF3, AFz, AF4, AF8, F7, F3, Fz, F4, F8; FC5, FC3, FCz, FC4, C5, C3, Cz, C4, C6. The posterior grid covered the two rows PO7, PO3, POz, PO4, PO8, and PO9, O1, Oz, O2, PO10. For both the anterior and the posterior grid the ANOVA factors were effort, PCI, row, and laterality (outer left, inner left, mid, inner right, outer right). To remove the influence of a possible prejudice-CN on the P2 amplitudes, they were measured relative to the ERP value at cue onset.

The CNV was measured as the mean amplitude across certain time intervals. The terminal CNVs (tCNV) before S2 (cue) and S3 (IS) were defined as the mean of the 50-ms interval before S2 and S3, respectively, at FCz (the maximum location of both CNVs); they were subjected to ANOVAs with the factors PCI (four levels) and effort (two levels). Further, a topographical analysis was conducted for both tCNVs by using a grid of 5 × 5 electrodes centered over the anterior scalp. This grid covered the five rows from antero-frontal to centro-parietal; in each row 5 electrodes, namely the midline and 2 (inner and outer) right and 2 (inner and outer) left electrodes were included. Hence, the five rows included AF7, AF3, AFz, AF4, AF8, F7, F3, Fz, F4, F8; FC5, FC3, FCz, FC4, FC6; C5, C3, Cz, C4, C6; CP5, CP3, CPz, CP4, CP6. The factors for both topographical CNV analyses were again effort, PCI, row, and laterality. For the FCz before S3, the topographical analysis was restricted to the three PCIs with a clear CNV (PCI 1200, 900, and 300).

A further ANOVA was conducted for assessing in more detail the development of the early CNV after the cue and for estimating the onset of the effort effect. This analysis was restricted to PCI 600, that is, the shortest PCI that produced behavioral improvement with effort. For this analysis, six time segments of 24 ms length (separated by gaps of 4 ms) after the P2, which covered a time range of 280 to 444 ms postcue, were computed for FCz (the numerical maximum of the entire postcue-CNv); the factors were segment (SEG1, ..., SEG6) and effort.

Finally, an ANOVA was conducted for testing a possible development of the CNV after the imperative stimulus (S3) for PCI 300. For this analysis, four time segments of 100 ms length after S3 were computed for FCz; the factors were segment (SEG1, ..., SEG4) and effort.

Results

Performance

The mean RT was 438 ms. It was 25 ms shorter in the effort trials (425 ms) than in the standard trials (450 ms), F(1,17) = 147.78, p < .0001. The RTs were reduced when the pre cue interval and hence the preparation time increased, F(3,15) = 38.96, p < .0001, e = .87 (Figure 1). Moreover there was a strong Effort × PCI interaction, F(3,15) = 13.37, p = .0001, e = .57, as shown in Figure 1, upper panel.

The simple effects for PCI at the two effort levels showed that the RT reduction with decreasing PCI was mainly present for the four PCI levels showed that the RT reduction with decreasing PCI was mainly present for the effort trials, F(3,51) = 30.68, p < .0001, e = .59, but also, although much smaller, for the standard trials, F(3,51) = 6.89, p = .0015, e = .81. For the effort trials, the only significant contrast was between PCI 300 and 600, F(1,17) = 28.05, p = .0001. For the standard trials, the contrast between PCI 900 and 600 was significant, F(1,17) = 7.49, p = .0141, whereas the other contrasts were not, F<1. The simple effects for effort at the four PCI levels showed that the effort effect was very large for each of the three longer PCIs, F > 74 each, whereas it was completely absent for the shortest PCI, F<1.

The error rate (Figure 1, lower panel) was high, namely 10.2%. It was higher for effort (13.0%) than for standard trials (7.2%), F(1,17) = 23.25, p = .0002. However, there was no main effect of PCI, F<1, and, more importantly, no significant Effort × PCI interaction, F<1, for the error rate. In particular, the error rate was virtually the same for PCI 600 (13.2%) and PCI 300 (13.8%) in the effort condition.

ERPs

Figure 2 shows the ERPs at the midline electrodes for PCI 900 as a typical example. After the S1, small exogenous potentials are
seen (P1, N1) that were not different for standard and effort trials. Before the cue, no clear CNV is seen. After the cue (S2) a frontal positivity/occipital negativity is seen ("P2/N2") that appears much larger for effort than for standard trials. Much later after S2, a parietal positivity ("P3b") is seen for effort trials only. After the P2/N2, a CNV develops with frontocentral maximum that also appears much larger for effort than for standard trials. Figure 3 presents the ERPs at FCz and Pz for all PCIs. FCz was chosen because the P2/N2 and the CNV were largest at FCz; Pz was chosen to highlight the P3b. A CNV before the cue ("precue-CNV") was only visible for PCI 300 (lowest panel). (This was true for all electrodes at the anterior scalp, which showed similar and small amplitudes.) The topographical analysis of the terminal precue-CNV over the frontal grid revealed a main effect of PCI, $F(3,51) = 6.11$, $p = .0028$, $\varepsilon = .82$, which confirms this view: The CNV was substantial only for PCI 300 ($-0.2 \mu V$), whereas it was negligible or even slightly positive for the other PCIs. Moreover there was a main effect of laterality, $F(4,68) = 7.28$, $p = .0017$, $\varepsilon = .54$, which shows that the precue-CNV was more negative over the right than over the left hemisphere. Finally there was a PCI $\times$ Side interaction, $F(12,204) = 10.31$, $p < .0001$, $\varepsilon = .33$, which reveals that this right preponderance was only present for PCI 300. The absolute maximum of the CNV was at FCz ($-1.3 \mu V$).

The ANOVA at FCz showed a strong main effect of PCI, $F(3,51) = 18.76$, $p < .0001$, $\varepsilon = .89$: The CNV amplitude was $-1.3 \mu V$ for PCI 300, whereas it was small for the other PCIs (0.4, 0.5, and $-0.4 \mu V$ for PCIs 1200, 900, 600, respectively).

The peak latency of the P2/N2 at FCz was 252 ms (SD: 35 ms). No effect on the latency was found for effort (standard: 253 (40) ms; effort: 251 (30) ms; $F < 1$) nor for PCI (252, 257, 256, and 242 ms for PCIs 1200, 900, 600, and 300; $F = 1.29$, n.s.). The latency was numerically shortest for effort trials in the PCI 300 condition (237 ms); however, the Effort $\times$ PCI interaction was not significant, $F < 1$. The amplitude maps of the P2/N2 peak are shown in Figure 4 for PCI 900 as an example (also there was no main effect or interaction with PCI; see below). The positive maximum is over the frontal scalp, whereas the negative maximum is over the occipital scalp. For effort trials, the P2 appears to be much stronger and extended to right frontal regions. The topographical analysis over the frontal grid showed a large main effect of PCI, $F(1,17) = 49.97$, $p < .0001$. Moreover a main effect of row, $F(3,51) = 14.78$, $p < .0002$, $\varepsilon = .48$, shows that the P2 was smaller at the central than at the frontal rows. A main effect of laterality, $F(4,68) = 19.09$, $p < .0001$, $\varepsilon = .55$, shows that the P2 was largest at the midline, but also larger at right than at left lateral electrodes, particularly for the outer pair. This was confirmed by contrasts (outer right vs. left: $F(1,17) = 20.02$, $p < .0003$; inner right vs. left: $F(1,17) = 3.52$, $p = .0780$. Finally a Row $\times$ Laterality interaction was found, $F(12,204) = 7.29$, $p < .0003$, $\varepsilon = .26$, that shows that the lateral asymmetry was larger for the frontal than for the fronto-central sites. The amplitude values for the P2 at the midline were (in microvolts; SDs in parentheses) FPz: 1.3 (1.6), AFz: 1.6 (1.9), Fz: 1.6 (2.0), FCz: 1.7 (1.9), Cz: 1.5 (1.6), Pz: 0.1 (1.3), POz: $-1.0$ (2.0), and Oz: $-2.2$ (2.2).

The topographical analysis over the occipital grid showed again a large main effect of effort, $F(1,17) = 50.53$, $p < .0001$. Moreover, a main effect of row, $F(1,17) = 19.09$, $p < .0004$, shows that the N2 was larger at the more posterior row. A main effect of laterality, $F(4,68) = 8.03$, $p = .0010$, $\varepsilon = .54$, shows that the N2 was larger at the lateral sites than at the midline. No difference between right and left electrodes was found (both outer and inner contrasts n.s.). The P3b following the cue, which was also much larger for effort than for standard trials, peaked about 250 ms later than the P2 (cf. Figures 2 and 3). Moreover, at Pz, the maximum of the P3b, the P2 was almost flat (see Figures 2 and 3 and above list of P2 values).

After the P2 a CNV develops, which grows monotonically up to the imperative stimulus (S3). As clearly seen in Figures 2 and 3, this CNV also appears larger for effort than for standard trials with the exception of the shortest PCI (300). For this PCI the

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Grand means ($n = 18$) of the ERPs at the midline electrodes between S1 (warning stimulus) and 1,200 ms after the imperative stimulus for standard (thin lines) and effort trials (heavy lines). S1: onset of the warning stimulus; S2: onset of the cue; S3: onset of the imperative stimulus. The main ERP components after S2 (P2/N2, CNV with tCNV and P3b) are labeled at their maximum electrodes.
CNV before the S3 has not yet developed, so there was no effort-
induced increase before S3. However, even for this short interval,
an effort effect seems to be present, but only after the onset of S3.

The amplitude maps of the terminal pre-S3 CNV (tCNV) are
shown in Figure 5 (for PCIs 1200, 900 and 600). The maximum
of the tCNV is located near FCz, and the tCNV is clearly larger
for effort than for standard trials. The topographical analysis
shows a main effect of effort,
\[ F(1,17) = 51.89, \ p < .0001, \ \eta^2 = .77. \]
Moreover, there was a strong PCI main effect, showing a marked reduction of the late CNV for PCI 300
\((-1.5 \mu V)\) compared to the other three PCIs, \(F(3,51) = 51.89, \ p < .0001, \ \eta^2 = .77. \)
Finally there was a strong Effort x PCI interaction, \(F(3,51) = 30.68, \ p < .0001, \ \eta^2 = .77. \)
The simple effects for the four PCIs (bottom of Table 1) showed that the
enhancement of the late CNV with effort was only present for the
three long PCIs. For PCI 300, the effect was reversed. Table 1
also shows that the CNV amplitude was virtually the same for the
three longer PCIs for standard as well as (although larger overall)
for effort. Figure 6 illustrates the variation of tCNV with effort
and PCI.

As suggested by Figure 3, the onset of the effort effect on the
CNV appears to occur particularly fast for PCI 600, that is, the
shortest PCI where effort caused an improvement of behavior.

The analysis of the tCNV at its maximum (FCz) was
conducted for all four PCIs to verify the differences of PCI 300
compared to the other three PCIs (Table 1). Again the CNV was
larger for effort than for standard trials, \(F(1,17) = 14.36, \ p = .0015. \)
Moreover, there was a strong PCI main effect, showing a marked reduction of the late CNV for PCI 300
\((-1.5 \mu V)\) compared to the other three PCIs, \(F(3,51) = 51.89, \ p < .0001, \ \eta^2 = .77. \)
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segment, which demonstrates the rise of the CNV, a marginal main effect of effort, and a Segment × Effort interaction, which shows different effort effects for the intervals. The simple effects for effort at the four segments (Table 2) were nonsignificant for the three early segments, but significant for the three late segments. The first segment with a significant effort effect (SEG4) corresponds to 368 to 392 ms postcue.

For PCI 300, the CNV had not developed before S3, but appears to be present, after S3, overlaid on the post-S3 ERP. Moreover the post-S3 CNV appears to show an effort effect (Figure 3, lowest panel). The post-S3 ANOVA at FCz first showed an increase from segments 1 to 4 (100 to 400 ms post-S3), which was, however nonmonotonous (-3.8, -5.3, -4.7, and -6.2μV; $F(3,51) = 11.11, p = .0004, \epsilon = .58$). Moreover, there was a clear main effect of effort, $F(1,17) = 10.37, p = .0050$, which confirms the post-S3 ERP to be larger for effort than for standard trials. Finally there was an Interval × Effort interaction, $F(3,51) = 6.66, p = .0043, \epsilon = .63$. The simple effects for effort at the four segments tended to be significant for SEG1 (0–100 ms post-S3): $F(1,17) = 3.24, p = .0898$, and significant for SEG2 to SEG4, beginning with SEG2 (100–200 ms post-S3): $F(1,17) = 5.97, p = .0258$.

In sum, before the cue there was almost no CNV; only for the shortest PCI there was a small CNV with right frontocentral maximum. After the cue a frontal positive and occipital negative component (P2/N2) and a CNV with right fronto-central maximum emerged. The P2/N2 was larger for effort than for standard trials for all PCIs. The terminal CNV before the imperative stimulus (S3) was larger in the effort than in the standard trials, but only, and in a very similar way, for the three long PCIs. The pattern of tCNV amplitude before S3 closely matched the performance pattern. The earliest onset of the effort effect was estimated to about 400 ms postcue. For the shortest PCI, the CNV and the effort effect developed after onset of S3, with the onset of the effort effect again at about 400 ms postcue.

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**Figure 4.** Amplitude maps for the P2/N2 at 252 ms after cue onset (baseline is ERP value at cue onset) for PCI 900 standard (upper panel) and effort trials (lower panel). The P2/N2 is positive (gray) over fronto-central areas with slight right preponderance (for effort trials) and negative over occipital areas (black); moreover, it is much larger for effort than for standard trials.

**Figure 5.** Amplitude maps for the terminal CNV (mean amplitude of a 50-ms time window before the imperative stimulus) for PCIs 1200, 900, and 600 standard (upper panel) and effort trials (lower panel). The tCNV is clearly maximum over FCz with slight right preponderance; moreover, it is larger for effort than for standard trials.
Discussion

The average RT scores (432 ms) closely matched our earlier results (Falkenstein, Hohnsbein, & Hoormann, 1994b) with trained subjects. In the present study, the subjects could, in fact, speed up their responses in the effort trials, but only in the three longer foreperiods (>300 ms), whereas there was no speed up in the short foreperiod (300 ms). The error rates were higher in the effort trials, but, in contrast to the RTs, this was a general effect for all foreperiods. This pattern cannot be solely explained by speed–accuracy trade-off; it is clear that the subjects could speed up their response in the 600-ms relative to the 300-ms foreperiod without further sacrificing accuracy, which remained constant. Hence, it can be concluded that the subjects, in fact, could improve their performance on a trial-to-trial basis, provided that the cue did not appear too late, that is, that the foreperiod was longer than 300 ms. Of course, some speed–accuracy trade-off may also have taken place, but this effect was overlaid by an additional true improvement of performance in the effort trials. These results fully replicate the earlier findings of Kleinsorge (2001).

In the average reference presentation, the ERPs after the critical stimulus, namely the cue, first showed a frontal positivity/occipital negativity with a mean latency of 250 ms (P2/N2). We cannot infer from the present data the exact sources of the P2/N2. However, the increase of the negative aspect at the occipital lateral versus the midline electrodes is compatible with bilateral sources in the visual cortex. However, the right predominance of the frontal aspect (which is not seen in the occipital aspect) suggests a further, possibly frontal source. Further studies with auditory and visual cues could help clarify the source of the P2/N2. Importantly, the P2/N2 was much larger for effort than for standard trials. This effect could be due to either the different probabilities of effort and standard cues (Legrain, Guerit, Bruyer, & Plaghki, 2002) or to a true effort effect on the P2/N2. The latter is suggested by early reports on task- and attention-related enhancements of the P2 (Näätänen, 1975) and P2 changes in children with attention deficits (Grünewald, Grünewald-Zuberbier, & Netz, 1978). If the P2/N2 was partly generated in the visual cortex, our results would suggest an enhancement of visual processing of the cue in the effort trials. Because cue probability and effort are confounded in the present study, the effect could also be due to the lower probability of effort versus standard trials. Hence, the important issue of a possible P2/N2 modulation with effort should be addressed in a future study with different probabilities of standard and effort trials, and with auditory in addition to visual cues.

Table 1. Descriptive Data and ANOVA Results for the Terminal CNV Preceding the Imperative Stimulus (S3) at FCz (Mean Amplitude in Microvolts in the 100-ms Time Interval before S3; Standard Deviations in Parentheses)

<table>
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<th>Effort</th>
<th>PCI</th>
<th>F</th>
<th>df</th>
<th>p</th>
</tr>
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<tr>
<td>Standard Effort</td>
<td>PCI</td>
<td>1200</td>
<td>900</td>
<td>600</td>
</tr>
<tr>
<td>Effort</td>
<td>1200</td>
<td>900</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>PCI</td>
<td>–4.5</td>
<td>(2.6)</td>
<td>–4.7</td>
<td>(2.7)</td>
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<td></td>
<td>51.89</td>
<td>3.51</td>
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Simple effects for effort at the four PCIs

<table>
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<th>Effort</th>
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<tbody>
<tr>
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<td>PCI</td>
<td>1200</td>
<td>900</td>
<td>600</td>
</tr>
<tr>
<td>Effort</td>
<td>1200</td>
<td>900</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>PCI</td>
<td>–3.2</td>
<td>(1.8)</td>
<td>–3.3</td>
<td>(1.8)</td>
</tr>
<tr>
<td></td>
<td>30.68</td>
<td>3.51</td>
<td>&lt;.0001</td>
<td>.78</td>
</tr>
</tbody>
</table>

Figure 6. Mean amplitude of the terminal CNV before S3 at FCz as a function of effort and precue interval. The tCNV shows a similar pattern as the RTs (Figure 1).
Table 2. Descriptive Data and ANOVA Results for the Entire CNV after the Cue (S2) for PCI 600, Separated into Six 24-ms Intervals (SEG1 to SEG6) Beginning 280 ms after Cue Onset (Mean Amplitude in Each Segment in Microvolts; Standard Deviations in Parentheses)

<table>
<thead>
<tr>
<th>Effort</th>
<th>SEG</th>
<th>F</th>
<th>df</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard</td>
<td>0</td>
<td>-1.3 (1.8)</td>
<td>-2.4 (3.3)</td>
<td>4.16</td>
</tr>
<tr>
<td>Effort</td>
<td>1</td>
<td>-0.7 (2.0)</td>
<td>1.6 (2.2)</td>
<td>2.6 (2.4)</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1.38</td>
<td>3.42</td>
<td>7.02</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>n.s.</td>
<td>n.s.</td>
<td>.0820</td>
</tr>
</tbody>
</table>

At about 550 ms after cue onset, a parietal P3 (P3b) is seen, which is much larger for effort than for standard trials. This can be explained by the well-known probability effect (e.g., Duncan-Johnson & Donchin, 1977). The duration of the P3b is much longer than that of the P2/N2, and its peak latency more than 250 ms later. Finally the P3b has the typical parietal maximum whereas the P2/N2 is almost flat at Pz. Hence, in our data, P2 is longer than that of the P2/N2, and its peak latency more than 250 ms later. Finally the P3b has the typical parietal maximum whereas the P2/N2 is almost flat at Pz. Hence, in our data, P2 and P3b can be safely differentiated.

After the P2/N2, a CNV with frontocentral maximum developed and culminated before the imperative stimulus. The late CNV was about 2 μV larger for effort than for standard trials, except for the shortest PCI of 300 ms, where a small effort-related CNV difference was only seen after the onset of the imperative stimulus. The enhancement of the CNV in the effort trials showed that the subjects could indeed control their effort on a trial-to-trial basis. However, this control obviously was too late in the shortest foreperiod of 300 ms, where no CNV difference before the imperative stimulus was seen, and no behavioral improvement occurred.

The similar values for the effort CNV before the imperative stimulus for the three long PCIs imply that the subjects have reached the same level of effort CNV in the long PCIs, even though there was much less preparation time in PCI 600 than in PCI 900 or 1200. This suggests that a certain CNV level is necessary to obtain the performance enhancement that is observed in PCI 600 versus 300. The inverted CNV effect for PCI 300 can be explained by the down-going flank of the P2/N2, which is larger in effort than in standard trials (Figure 3, lowest panel).

In the 600 ms PCI, which was the shortest foreperiod that produced an improvement in performance and which showed the shortest onset of the effort effect in the grand mean data, the latency of the effort effect in the CNV was estimated to be 350–400 ms. Hence, it appears that our subjects could allocate extra processing resources in less than 400 ms after a cue that signaled the effort condition in order to improve their performance. This high speed seems to be necessary, particularly in case of short PCIs, as our PCI 300 data suggest that a CNV enhancement has to be established before stimulus onset to ensure an improvement of all processing steps including stimulus detection and identification. Interestingly however, for PCI 300, an effort effect was also seen, and also beginning at about 400 ms postcue. Hence it appears that differential preparation can continue even when the task following the imperative stimulus is already being done.

The minimum time for activating extra effort is likely to depend on the time for discriminating the two cues. Although we chose highly discriminable color cues, which can be processed relatively fast, it is viable that with other cues (e.g., location; cf. Hillyard & Münte, 1984), an even faster CNV effect might be possible.

A surprising finding was the small or even absent CNV before the cue. For the longest foreperiod (PCI 1200), this is trivial, but not for the shorter ones. For PCI 600 and 300, the CNV is still very small, although (more than) half of the foreperiod has elapsed at the moment the cue is presented. Hence, it appears that the subjects did not invest much preparatory effort before the cue. One reason for this lack of effort investment is the uncertainty about the quality (standard/effort) and the exact timing of the upcoming cue, because the PCI was randomized within a block. The cue will be more probably (80%) the standard, so that a strategy to invest effort in advance (i.e., before the precue) may appear suboptimal. Furthermore, it is well known that uncertainty about the exact moment of a taskrelevant stimulus strongly reduces CNV amplitude (e.g., Desmedt & Debecker, 1979). Nevertheless it is astounding that even in the PCI 600 and 300 conditions, when the timing can be reasonably well predicted, the CNV is that small in our
experiment. Hence it appears, that a CNV is only built up when it is really necessary. A further explanation for the small precue CNV may be that the cognitive tasks, which are linked to the cue, namely the discrimination between the blue and the red color and the decision whether or not to invest more effort, does not require much effort.

Our results confirm the hypothesis of Freude et al. (1988, 1989, 1995) that a negative slow wave with frontal preponderance (the CNV) occurs before a cognitive task that is related to the performance of the expected task. However, in our paradigm, several preparatory processes are likely to occur before the imperative stimulus, namely stimulus, cognitive, and motor preparation, which could have all been influenced by effort. Our CNVs (both before the cue and before the imperative stimulus) showed a right preponderance, which is typical for the stimulus-preceding negativity, that reflects pure cognitive preparation (Brunia, 1988). This suggests that also our tCNV reflects cognitive preparation to a considerable degree. Nevertheless, in the planned follow-up study (see above) we want to assess effort-related effects on the CNV in a pure motor task (simple reaction) and in a pure cognitive task without motor requirements (e.g., mental arithmetic).

In our study, the CNV was frontocentrally located also shortly before the imperative stimulus. However, for the longer PCIs, the terminal CNV slightly shifted to a more central location. Also the tCNV amplitude was slightly smaller for PCI 1200 than for PCI 900 and 600. This suggests a decrease of general (frontal) and a preponderance of task-specific preparatory activity (central/parietal) in the final phase. Hence, our results are in line with the models of Rockstroh, Elbert, Canavan, Lützenberger, and Birbaumer (1989) and Brunia (1999), who all suggest that the primary preparatory mechanism is mediated by a medio-thalamo-frontal system, which in turn organizes the preparation of other, task-specific areas. In our results, the activity and the timing of the general frontal system may be reflected in the frontocentral CNV. However, our results appear to differentiate at least two frontal sources of our CNVs; its primary source may be located in the central zone, including premotor, supplementary, and cingulate motor areas (Lamarche, Louvel, Buser, & Rektor, 1995), for example, in areas that control movement preparation. A further source, which is reflected in the right frontal part of the CNVs and also of the P2/N2, may be located in the right prefrontal cortex. In our planned study, we want to use source estimation techniques to further elucidate the pattern of CNV sources.

Fronto-central CNVs are also reported in the literature in conditions that require high effort. For example, Lorist et al. (2000) conducted a task in which predictable task shifts alternate with task repetitions. Shift trials were experienced as more effortful and resulted in longer RTs. Immediately before such a task-shift, a large frontal negative slow wave occurred, whereas before a task repetition, a parietal negativity was seen. The frontal negativity was strongly reduced with mental fatigue, which was accompanied by a decrease in performance in shift trials. This adds to the evidence that frontal slow negativities, as also seen in our study, are related to effortful executive processes that modulate or change ongoing preparatory processes.

In conclusion, our data show that subjects are able to allocate additional processing resources to a task on external demands on a trial-to-trial basis within less than 400 ms. This resource allocation is reflected in the enhancement of a frontal positivity/occipital negativity (P2/N2), the source of which is probably located in the visual cortex, and of a negative slow wave with frontocentral maximum; both occur both after the informative cue. When the residual preparation time is sufficient, this slow wave is seen as CNV before the imperative stimulus. In this case, effort allocation results in performance improvement. When the residual preparation time is too short (our PCI 300 condition), performance cannot be improved; nevertheless, effort allocation (as reflected in CNV enhancement) still continues even when the task is already being done. The CNV results suggest an executive mechanism possibly located in the frontal lobe by which subjects can intentionally and quickly regulate the assignment of resources to a task. A practical implication of our results is the possibility of measuring effortful preparation in varying real-life situations.

**REFERENCES**


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