Motor programming of response force and movement direction

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Abstract

Effects of movement advance information were assessed on the prestimulus amplitude of the lateralized readiness potential (LRP), on the contingent negative variation (CNV), and on reaction time (RT). In a precuing paradigm with movement parameters hand, direction, and force, partial precues provided advance information about either hand alone, hand plus force, or hand plus direction, and the full precue specified all response parameters. The full precue produced the shortest RTs and the largest CNV amplitude, precuing hand and force or hand and movement direction produced somewhat slower RTs and a somewhat smaller CNV amplitude, and precuing only hand yielded slowest RTs and the smallest CNV amplitude. In contrast, the LRP amplitude was largest for the full precue and was the same for the remaining precues. The CNV appears to index the central assembling of a motor program, and the LRP represents the implementation of the program at more peripheral levels.

Descriptors: Motor programming, LRP, CNV, Readiness potential, Reaction time, Response force

The introduction of event-related brain potentials (ERPs) in the study of movement preparation has provided new approaches and insights into what had previously been an exclusively behavioral field. The most successful approach in cognitive psychology to analyze the nature of movement preparation employs the precueing technique developed by Rosenbaum (1980, 1983). This technique is a variant of a choice reaction time (RT) task, in which each of the possible responses is associated with a single imperative stimulus. Before the onset of the stimulus, a precue conveys information about certain movement parameters. Usually, RT decreases with the amount of advance information provided. From the relation between advance information and the corresponding RT savings, cognitive psychologists hoped to learn more about motoric preparation and the nature of motor programs (e.g., Rosenbaum, 1980). However, this approach was criticized by Goodman and Kelso (1980) who argued that the RT saving observed with this technique does not reflect a genuine motor effect but rather the facilitation of response selection at a premotoric level. The debate on whether the RT saving reflects a genuine motoric effect could not be settled with the traditional behavioral RT measure because the motoric portion of RT is not directly observable.

In resolving this controversy, a new measure, the lateralized readiness potential (LRP), has recently been used (Leuthold, Sommer, & Ulrich, 1996); there is strong evidence that the LRP provides a specific index to trace the time course of motor activation (cf. Coles, Gratton, & Donchin, 1988; De Jong, Wierda, Mulder, & Mulder, 1988; Miller & Hackley, 1992). Experiments employing LRP often involve a two-choice RT task in which a precue informs the participant about the responding hand and a subsequent imperative stimulus tells the participant that the response should now be made. During the interval between the precue and the imperative stimulus, the motor readiness potential exhibits greater negativity over the motor cortex contralateral to the responding hand, suggesting that this asymmetry reflects preparation of a specified motor action (e.g., Kutat & Donchin, 1980). Similar results have been found when the precue merely indicates which hand is more likely to have to respond (Gratton et al., 1990). Therefore, the asymmetry of the readiness potential captured by the LRP qualifies as an index for the preparation of specific motor acts. Thus, by examining how precue information affects the waveform and the timing of the LRP, the mechanisms underlying response preparation may be inferred. The purpose of this present study was to extend this approach. We investigated whether the amplitude of the prestimulus LRP increases systematically with the amount of advance information, as some hypotheses on motor preparation in precuing studies propose.

Ulrich, Moore, and Osman (1993, 1994) suggested two hypotheses about the prestimulus LRP: abstract versus muscle-specific motor preparation. They employed a precue that prespecified either the left or the right index finger but not its movement direction (flexion or extension). Although, participants did not know the movement direction of the prespecified index finger before the appearance of the imperative stimulus, the advance information conveyed by the precue was sufficient to elicit a clear prestimulus
LPR. Hence, the authors concluded that partial information about hand is sufficient to produce a prestimulus LRP. This result is consistent with both an abstract and a muscle-specific motor hypothesis of motor preparation. According to the abstract preparation hypothesis, the LRP merely reflects the selection of the response hand at an abstract level of motor organization, and therefore it is insensitive to further response preparation that might be performed for the selected hand (e.g., preparation of movement direction or response force). Alternatively, the muscle-specific motor preparation assumes that the LRP reflects not only abstract limb selection but also the selection and proper adjustment of response-specific muscle groups. This hypothesis is consistent with hierarchical theories of movement specification (Rosenbaum, 1985). Accordingly, movement preparation proceeds from general level units (such as body side) towards specific level units (such as muscle force) within the motor program hierarchy. The LRP amplitude, therefore, might reflect how far the specification process has progressed within this hierarchy before the imperative response stimulus appears.

Recently, Leuthold et al. (1996) provided some evidence for such a hierarchical view. These authors extended the study of Ulrich et al. (1993) by including additional precue categories. As in this previous study, imperative stimuli were mapped one-to-one to four response alternatives consisting of flexions or extensions of the right or left index finger. The imperative stimulus was preceded by a precue belonging to one of four precue classes. One precue, the full precue, reduced the four response alternatives to one. The no-information precue provided no advance information. The hand precue informed about the response finger (left vs. right index finger) but not about movement direction, whereas the direction precue gave advance information about movement direction (extension vs. flexion) but not about the responding hand. Thus, the full precue allowed the prespecification of both movement parameters hand and direction, the hand and direction precues prespecified only one parameter, and the last precue provided no information.

Consistent with the hierarchical view of movement preparation, the prestimulus LRP amplitude was largest for the full precue, smaller for the hand precue, and not affected by the no-information and the direction precue.1 A corresponding RT saving accompanied these LRP findings.

The present study was designed to refine and to extend these findings. Specifically, all precue categories in the present study allowed hand preparation but the amount of advance information differed over precue categories. This design provides a more rigorous test of the hypothesis whether the prestimulus LRP amplitude fully reflects the amount of hand preparation, as suggested by the results of Leuthold et al. (1996). In the present study, we employed eight imperative stimuli assigned to eight response alternatives. These alternatives consisted of either weak or strong isometric extensions or flexions with either the left or right index finger. A precue occurred 1.4 s before the imperative stimulus. It provided partial advance information about hand only (left vs. right), about both hand plus movement direction (extension or flexion), or about hand plus required response force (weak vs. strong) or it gave full advance information about hand, movement direction, and response force. Thus, the precue conveyed advance information on one, two, or three orthogonal movement dimensions (hand, direction, force). This design allows one to distinguish among various hypothesis of the prestimulus LRP amplitude.

First, if the LRP represents an abstract level of response preparation that merely signals hand preparation but no further preparation for the selected hand (such as the preparation of movement direction or response force), the prestimulus LRP amplitude should not vary with precue category. Second, if LRP reflects a parallel programming process of several parameters, the prestimulus LRP amplitude should increase with the number of precued parameters. Third, if LRP indexes a hierarchical organization of response preparation, then advance information about response force cannot be used for response preparation as long as information about movement direction is missing, for example, because force cannot be specified as long as extensor and flexor muscles are unspecified (Megaw, 1972; but see also Zelaznik, 1981). According to this hypothesis, advance information in response force in addition to hand information should not further enlarge the prestimulus LRP. Finally, a stronger version of a hierarchical system is also conceivable, where the LRP amplitude only shows a further increase when a response within the prespecified hand can be fully pre-specified. For example, a muscle-specific preparation hypothesis would suggest this possibility. In this case, the proper specification of the appropriate muscle group may be possible only if information about both direction and force is available. Thus, only the full but neither the force nor the direction precue should further enhance the prestimulus amplitude of the LRP.

We also assessed potential effects of partial advance information on the nonlateralized portion of the ERP during the prestimulus period. Precue information may exert a somewhat different effect on lateralized than on nonlateralized ERP components, of which the latter may reflect more general aspects of movement programming (e.g., Vidal, Bonnet, & Macar, 1995). In warned RT tasks, a sustained negativity develops after the warning signal during the foreperiod interval. This negativity is called the contingent negative variation (CNV; Walter, Cooper, Aldridge, McCallum, & Winter, 1964). It consists of two waves, an early and more frontocentrally dominant wave and a later more centroparietally dominant wave (cf. Rohrbaugh & Gaillard, 1983). The early CNV wave seems to reflect the orienting properties of the warning signal (Loveless & Sanford, 1974). Traditionally, the late CNV wave was thought to reflect motor preparation and therefore to be identical to the readiness potential (Rohrbaugh & Gaillard, 1983). Although, the largest part of the late CNV wave is certainly a readiness potential, more recent studies indicate that nonmotoric components also contribute to it (see Brunia, 1993).

The motoric component of the late CNV appears to be sensitive to the amount of partial advance preparation, as documented by MacKay and Bonnet (1990). Precues provided advance information about movement direction (elbow flexion vs. extension) or response force (weak vs. strong). As in other precue studies, RTs decreased with increases in the amount of information conveyed by the precue, and the CNV amplitude showed an analogous precuing effect. Thus, the CNV may provide a more general index of motor preparation and thus dissociate from the LRP.

**Method**

**Participants.** Four women and 12 men (mean age = 32 years, range = 26–43 years) participated in a single session taking about 2 hr. They received for their participation either partial fulfillment

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1The direction precue by definition cannot elicit a prestimulus LRP because response preparation of movement direction applies to both index fingers and thus cannot affect the lateralized portion of the readiness potential. Hence, any preparation that applies equally to both hands cannot be captured by the LRP.
of a curriculum requirement or money (10 DM/hr). All participants had normal or corrected-to-normal vision. Mean handedness score (Oldfield, 1971) was 58; three participants were lefthanded.

**Procedure.** Two practice blocks were followed by 16 blocks of 40 trials each. Blocks were separated by a short rest. Participants were instructed to utilize precue information to shorten RT but not to initiate a movement before the imperative stimulus appeared. There were eight different response stimuli associated with eight responses. The eight response alternatives consisted of weak or strong isometric extensions or flexions of the right or left index finger. Precues and response signals specified these response alternatives in a highly compatible manner.

Each trial started with the presentation of the fixation cross in the center of the computer screen and four open squares (Figure 1). This basic arrangement remained visible until the offset of the imperative stimulus. Precue information was added to the display 450 ms later. For example, when the left upper square was filled, it indicated that a flexion with the left index finger would be required and thus the participant could start preparing this response. If, in addition, the height of the left upper square would also change, the participant was not only informed about the upcoming movement but also about the required force level for this movement. An increased height signaled a strong response, whereas a decreased height indicated a weak response. More specifically, the two right squares signaled a movement with the right index finger, and the two left ones indicated movement with the left index fingers. The two upper squares indicated an index finger extension, and the two lower squares indicated an index finger flexion. Large rectangles indicated a strong response, and small rectangles indicated a weak response (the complete set of precue combinations is defined below). After a constant period of 1,500 ms the imperative stimulus was superimposed on the precue pattern and remained visible for a further 1,030 ms, after which the information on the screen was removed.

Participants were asked to perform the required response as fast as possible but to avoid response errors. No-go trials randomly appeared with a probability of 1/11 to prevent premature responses. After a correct response, the next trial started 5,590 ms after the onset of the precue stimulus. After a wrong response, feedback was provided on the screen 50 ms after stimulus offset. This feedback consisted of one of the following messages: (a) *Falsch* (wrong) if a wrong response alternative was used or if the participant responded with both hands; (b) *Zu früh* (too fast) if RT was less than 100 ms; (c) *RT > 1 sek* if there was no response within 1 s, and (d) *Kraft !!* (force) if response force was either too weak or too strong. If a response occurred in a no-go trial the feedback **NoGo!!!** appeared. Feedback information was displayed for 1,110 ms, and 1,900 ms later the next trial started with the presentation of the fixation cross. Mean RT and percentage of response errors were provided as feedback after each block. Participants were asked to keep their eyes on the fixation cross and not to blink as long as it was visible.

**Stimuli and precues.** Ambient light was kept at a low level. A constant viewing distance of 1 m was provided by a fixed chin rest.

The warning stimulus consisted of four small gray open squares (0.17 × 0.23) on a black background (see Figure 1). The centers of the squares were placed on the corners of an imaginary rectangle (0.40 × 0.52). The same arrangement served as precue with the only exception that advance information about response hand and about movement direction was provided by the filling pattern of the squares and about response force by changes in height. Filling and height reduced the possible response alternatives. The imperative stimulus was based on the configuration of the precue. On go trials, the response-determining rectangle became red and its height indicated the required force. In no-go trials, the filled squares became open again, i.e., four small open squares were displayed.

There were four precue categories. First, the full-information precue (FDH) reduced the possible responses to one. In this case, three squares were shown open and the response-indicating rectangle was filled and its height was small or large. For example, a small filled rectangle in the left upper quadrant signaled a weak extension response of the left finger. Second, the force-hand precue (FH) specified response finger and force but not movement direction. For example, two filled left rectangles gave advance information about a left finger response and their height specified response force, that is, small rectangles specified a weak response and large rectangles specified a strong response. Third, the direction-hand precue (DH) provided advance information about the response finger (left vs. right index finger) and movement direction. For example, a flexion movement of the left finger was presupposed by a filled lower left square of the same height as the remaining empty squares. Finally, the hand precue (H) provided advance information about the response finger. Two filled left squares indicated a left-finger response and two filled right squares indicated a right-finger response. The imperative stimulus commands a strong extension response with the left index finger.

![Figure 1](image-url). The temporal sequence of events in a single trial. In the example shown, an extension movement with the left index finger is precued. The imperative stimulus commands a strong extension response with the left index finger.
indicated a right-finger response. Excluding no-go trials, there were 32 trial types that resulted from the factorial combination of precue category by response alternative. A session included 20 replications of each trial type. All types (viz. conditions) were completely randomized across the 640 go trials of the experiment. On average, 58 (SD = 2.4) go trials were randomly replaced by no-go trials.

Response keys. Response force was measured by means of force-sensitive keys. A cantilever beam with minimal movement (55 × 20 × 2 mm) was held by an adjustable clamp at one end while the other end remained free. Strain gauges were attached near the fixed end of the leaf spring. One force key was used for each index finger. The fingertip was located in an adjustable thimblelike holder attached to the free end of the leaf spring. The force key allowed for near-isometric recordings of index finger flexions and extensions. RT was defined as the interval from stimulus onset until response force exceeded the criterion of 40 cN from the baseline force level in either the negative or positive direction (extension and flexion, respectively). Baseline force was defined as the mean force level during a 100-ms interval before precue presentation. Each force key was mounted on a board. Both forearms and palms rested comfortably on the boards such that any body movements other than index finger movements were minimized. For each participant, maximal response force was determined separately for extension and flexion movements and for each hand to determine individual threshold values for weak and strong responses. When a weak response was required, the peak of the force output had to be less than 30% of maximum voluntary force (yet larger than the 40-cN criterion force to measure RT). In contrast, when a strong response was required, peak force had to be greater than 30% of maximum voluntary force.

Electrophysiological recordings. The electroencephalogram (EEG) was recorded at Fz, Cz, and Pz (Jasper, 1958) with the right earlobe as a common reference. Bipolar recordings were made from C3− and C4+. These sites were located 4 cm to the left and right from Cz along the interaural line. Horizontal and vertical electrooculograms (EOG) were recorded from the outer canthi and from above and below the right eye. Time constants of all channels were 10 s, and low-pass filters were set at 40 Hz (roll-off 12 dB/octave). EEG and EOG recordings were made with Grass E5SH Ag/AgCl electrodes and TECA electrode electrolyte. All signals were digitized at a rate of 100 Hz for 2,680 ms, starting 200 ms before precue onset (see Figure 1).

Data analysis. The LRP was computed according to the following method (cf. Coles, 1989). Differential recordings were made between C3−(t) and C4+(t) at time t to eliminate all activity that was symmetrically distributed over centrotemporal recording sites. For right-hand responses, the difference DR(t) = C3+(t) − C4−(t) was recorded, whereas for left-hand responses the polarity was inverted to obtain the difference DL(t) = C4+(t) − C3−(t). To eliminate all nonmotoric asymmetries, the difference waveforms DL(t) and DR(t) were averaged over all trials within a single condition and the LRP(t) was computed as the mean of both average waveforms: LRP(t) = [mean DL(t) + mean DR(t)]/2. Accordingly, the LRP is negative when the electrical scalp potential is more negative over the motor cortex that activates the correct hand and positive when the incorrect motor cortex is activated.

Horizontal EOG (hEOG) was computed analogously to the LRP to assess the effect of possible electroocular artifacts on the LRP. Because the retina is more negative than the cornea, eye movements towards the lateralized response stimulus or towards the responding hand may mimic LRP activity. Previous studies have indicated that ocular potentials contribute to no more than 20% of the potentials at central scalp sites (e.g., Elbert, Lutzenberger, Rockstroh, & Birbaumer, 1985), that is, 20% of hEOG activity may propagate to the LRP.

For RT and EOG analysis, all trials with ocular artifacts or with incorrect responses and any trial immediately following an error were discarded. For artifact rejection, a threshold of 100 μV in all EOG channels was chosen, and all trials in which this threshold was exceeded during the recording epoch were discarded.

Design. Statistical analyses were performed by means of Huynh–Feldt-corrected repeated measures analyses of variance (ANOVA). For RT and force analysis the within-subject variables were precue category (FDH vs. FH vs. DH vs. H), force (weak vs. strong), movement direction (flexion vs. extension), and hand (left vs. right). For LRP analysis, data were pooled over the variables hand, movement direction, and force.

Results

Accuracy and reaction time. As required, participants responded on average with 4.21 N and 28.41 N in the weak and strong force conditions, respectively. There were 9.9% anticipations in no-go trials. In go trials, 2.7% of the responses were errors, comprised of 0.7% misses (RT > 980 ms), 0.3% anticipations (RT < 100 ms), 0.4% force errors, and 1.3% wrong keypresses.

Figure 2 depicts mean RT and the percentage of correct trials for the full factorial design. ANOVA yielded a main effect of precue category, F(3, 45) = 117.1, ε = 0.73, p < .001. Planned comparisons revealed the following ordering of mean RT for the four precue conditions: FDH (340 ms) < DH (433 ms) = FH (441 ms) < H (471 ms). Force produced a significant effect, F(1, 15) = 90.4, p < .001; strong responses (390 ms) were faster than weak ones (453 ms). This force effect on RT was larger for right-hand than for left-hand responses, F(1, 15) = 9.8, p < .01. The significant Precue Category × Force interaction, F(3, 45) = 19.5, ε = 1, p < .001, was due to a decrease of the force level effect in RT when advance information about force was provided. Movement direction produced a main effect, F(1, 15) = 15.7, p < .01; extensions (411 ms) were faster than flexions (432 ms). The interaction of Precue Category × Movement Direction was significant, F(3, 45) = 17.6, ε = 1, p < .001. This result indicates a reduced RT difference between flexions and extensions when advance information about movement direction was provided. RT and response errors covaried in the same direction for FDH, FH, DH, and H. Thus, the obtained precue effect cannot be attributed to a speed/accuracy trade-off.

Prestimulus LRP amplitude. The average LRP for each precue category is shown in Figure 3. As expected, a clear LRP was elicited after precue onset during the period indicating preparation of the correct response hand. About 500 ms after precue onset, the prestimulus LRP became more negative for FDH than for the other precue conditions. For statistical analysis, the amplitude of prestimulus LRP was averaged in the interval from 210 to 10 ms prior to the onset of the imperative stimulus. Average LRP amplitudes were referred to a 200-ms baseline before precue onset. Two-tailed t tests showed that all LRP amplitudes deviated significantly from zero: for FDH, t(15) = −6.0, p < .001, for FH, t(15) = −5.9, p <
One-tailed tests indicated that mean amplitude for FDH~$\sim$~2.10 mV was larger than that for FH~$\sim$~2.06 mV, DH~$\sim$~2.05 mV, and H~$\sim$~2.05 mV, ts~<~1.7, ps~<~.05. Pairwise comparisons indicated no significant differences in mean LRP amplitudes among the conditions FH, DH, and H, ts~<~1. To assess whether the effects on prestimulus LRP could have been due to eye movements, hEOG was analyzed in exactly the same way as the LRP. Precue category did not produce a significant main effect on hEOG, $F$~<~1, FDH~$(-2.3 \mu V)$ = FH~$(-1.9 \mu V)$ = DH~$(-1.8 \mu V)$ = H~$(-2.0 \mu V)$. Thus, it is implausible that the enhanced prestimulus LRP for condition HDFP was caused by hEOG activity.

**Figure 3.** Lateralized readiness potential (LRP; upper panel) and horizontal electroocular (hEOG) activity (lower panel) for each precue category. S1 and S2 indicate precue and imperative stimulus, respectively.
The present results rule out some of the hypotheses on the functional meaning of the prestimulus LRP. First, according to the abstract preparation hypothesis, the prestimulus LRP might merely reflect the selection of hand side and thus should be uninfluenced by any further specification of the selected hand (e.g., the additional preparation of response force or movement direction). The present results do not support this hypothesis because it holds that the prestimulus LRP should not differ across the precue categories employed in this study. Thus, the present results provide clear evidence against the view that the LRP amplitude merely indexes an abstract preparation of lateralized response channels (Sommer, Leuthold, & Ulrich, 1994). This conclusion also agrees with the prestimulus LRP results reported by Leuthold et al. (1996).

Second, the present results also do not support the notion that the LRP amplitude indexes a parallel programming process. According to this hypothesis, prestimulus LRP is expected to increase steadily with the number of precued movement dimensions. However, such a highly differential precue effect was not obtained.

Third, the LRP does not seem to index a hierarchical organization that requires the specification of movement direction before information about response force can be utilized for response preparation. According to this hypothesis one would expect that advance information about movement direction in addition to hand information would further enlarge the prestimulus LRP. However, this prediction was not confirmed. The present LRP results are best explained by the stronger version of the hierarchical preparation hypothesis according to which the next level unit after the hand node within the hierarchy can only be activated after information on both response force and movement direction is available.

Although this tentative hypothesis provides a possible explanation for LRP activation, it cannot account for the differential precue effect on RT. Recent evidence, however, indicates that RT and LRP are not equivalent measures of response preparation (Miller, Coles, & Chakraborty, 1996). Within a single experiment, Miller et al. (1996) found clear effects of response priming in RTs but no evidence of response preparation in the LRP. They interpreted this dissociation as evidence that response priming indexes response preparation at a central level, which may be present even without response preparation at a later level in the stimulus–response chain, which is indexed by the LRP. This conclusion was further corroborated by Band and Miller (1997).

The present results on the nonlateralized portion of the motor readiness potential, the CNV, have some bearing on the dissociation issue. The late component of the CNV revealed a differential precueing effect analogous to the one on RT; the amplitude of the prestimulus amplitude of CNV grew steadily with the amount of advance information. Although, precue information had a profound effect on RT and the late CNV component, an analogous effect was not observed for the prestimulus LRP. Consistent with previous precueing studies (e.g., Goodman & Kelso, 1980; Leuthold et al., 1996; Rosenbaum, 1980), a differential precueing effect on RT was obtained; RT decreased systematically with the amount of advance information. In contrast, however, a similar differential effect on prestimulus LRP failed to materialize. Consistent with the study of Leuthold et al. (1996), the prestimulus amplitude was larger when advance information completely specified the response (i.e., hand side, movement direction, and response force) than when it only specified the responding hand. However, additional advance information about movement direction and response force did not affect the LRP amplitude. Only the combined advance information of all three movement parameters enlarged the amplitude of the prestimulus LRP.
movement advance information. Thus the precuing effect on the CNV appears to reflect those central preparation processes involved in the savings of RT. In summary, a large portion of response preparation, in particular the portion that speeds up a response, appears to be related to central mechanisms.

This central response preparation seems to be consistent with a parallel organization of response preparation (Rosenbaum, 1980) because any advance information about the forthcoming movement increases the CNV. However, only a part of this parallel process seems to be associated with more peripheral preparation, as indexed by the LRP. For example, although advance information about response force and movement direction have additive effects (because they can be specified in parallel) on central programming mechanisms, this advance information may only be of use for the preparation of more peripheral processes after the central programming mechanism has integrated both effects into a single code. If peripheral preparation processes cannot proceed until such a compound code is available from central preprogramming processes, the peripheral preparation mechanisms exhibit hierarchical processing of advance information. More generally speaking, two phases of motor preparation may exist: the assembling of a motor program and its implementation (e.g., Rosenbaum, 1985). Thus, the CNV may reflect the former whereas the LRP indicates activation of the latter phase of movement preparation.

This two-phase process of response preparation accounts also for the LRP results of Leuthold et al. (1996). In that study, participants received advance information about hand, movement direction, or both. In contrast to the present study, however, those participants responded with the same force level in each trial. Hence, response force was not specified anew in each trial (i.e., response force was a default parameter). Thus, the hand precue of Leuthold et al. is functionally identical to the FH precue in the present study. Analogously, their hand-direction precue is functionally identical to the FDH precue. As one might anticipate from the two-phase preparation process, Leuthold et al. observed a larger LRP amplitude when response force, movement direction, and hand information could be integrated into a compound code that further enhanced peripheral response preparation. Thus, the two-phase model seems to apply whether or not response force is considered a default or variable movement parameter.

In sum, the results of the present study indicate that the combined use of LRP, CNV, and RT provides a deeper understanding about which aspects of response preprogramming are associated with central or more peripheral processes within the central nervous system. The LRP seems to index a peripheral preparation organization that receives compound codes to advance preparation from a central preparation system, which seems to reflect a parallel organization and mainly be responsible for the precue effects on RT. Further research with different movements is clearly necessary to confirm the generality of this conclusion.

The present CNV results seem to be in conflict with those reported by Van Boxtel and colleagues (Van Boxtel & Brunia, 1994a, 1994b; Van Boxtel, van den Boogaart, & Brunia, 1993). The original study (Van Boxtel et al., 1993) employed a conventional S1-S2 paradigm. Their participants were to attain a fixed force level at two different speeds, that is, either as fast as possible or somewhat less fast. An instruction stimulus indicated the speed level and was presented either at S1 or at S2. An enhanced CNV amplitude was found when the instruction stimulus was presented at S2 as compared with S1. Two follow-up studies confirmed this main result (Van Boxtel & Brunia, 1994a, 1994b).

Thus, the essence of their findings is that when participants have advance information about the upcoming movement (viz. when the instruction stimulus is paired with S1) the amplitude of the late CNV wave is smaller than when no advance information is available (viz. when the instruction stimulus is paired with S2). In our study, the opposite precue effect was obtained on the late CNV wave, and thus the results appear to be contradictory. However, a closer look suggests that the precue effect in Van Boxtel et al.’s (1993) study reflects a nonmotoric effect. Their precuing effect is frontally dominant and thus seems to reflect a nonmotoric component of the late CNV wave, as the authors themselves asserted. However, in our study there was virtually no precue effect at Fz, but there was a strong one at Cz and Pz. This centripetal effect resembles the readiness potential, which is related to motor preparation (D6ecke & Kornhuber, 1977).

We assume that these discrepant results are due to one or more procedural differences between Van Boxtel et al.’s (1993) and Van Boxtel and Brunia’s (1994a, 1994b) studies and the present experiment. For instance, Van Boxtel et al. employed a 4-s period between S1 and S2, whereas we employed a similar period of only 1.5 s. It is likely that motor preparation is difficult to maintain or to build up with long foreperiods, because the temporal predictability of S2 deteriorates with increasing foreperiod duration (cf. Niemi & Näätäinen, 1981). Furthermore, maintaining motor preparation over long periods is difficult (Niemi & Näätäinen, 1981) and can even be experienced as an aversive state (Gottsdanker, 1975; Näätäinen, 1972). Hence, the late CNV wave associated with long foreperiods might predominantly reflect sensory processes related to the anticipation of the stimulus pattern. Thus, increasing stimulus uncertainty may well enhance stimulus anticipation and, consequently, the amplitude of the late CNV and would account for Van Boxtel et al.’s data and explain the divergent results.

There is another considerable methodological difference. Van Boxtel et al. (1993) and Van Boxtel and Brunia (1994a, 1994b) blocked their experimental conditions across trials, whereas in our study conditions were randomly mixed. Participants may refrain from a differential motor preparation when conditions are blocked because the speed advantage resulting from partial motor preparation might only be recognized by a participant when conditions are randomly mixed. MacKay and Bonnet (1990) also reported that the amplitude of the late CNV increases with the amount of movement advance information; as in the present study, conditions were mixed across trials in their study. In conclusion, the discrepant CNV results seem to be due to important methodological differences, which favor nonmotoric effects in the studies of Van Boxtel et al. and Van Boxtel and Brunia but motoric effects in our study.

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