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Phasic heart rate responses to performance feedback in a time production task: effects of information versus valence

Frederik M. van der Veen [a,c,*], Maurits W. van der Molen [a], Eveline A. Crone [a], J. Richard Jennings [b]

[a] *Department of Psychology, University of Amsterdam, Roetersstraat 15, 1018 WB Amsterdam, The Netherlands*
[b] *Western Psychiatric Institute and Clinic, E1333, 3811 O'Hara Street, Pittsburgh, PA 15213, USA*
[c] *Department of Psychiatry and Neuropsychology, Maastricht University, P.O. Box 616, 6200 MD Maastricht, The Netherlands*

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Abstract

This study examined the cardiac concomitants of feedback processing in a time production task derived from [Mittner et al., J. Cogn. Neurosci. 9 (1997) 788]. Participants performed the time production task (i.e. 1-s intervals) under two conditions. In the experimental condition, feedback informed them that the produced interval was within or outside the acceptable range (too long or too short). In the other, yoked-control, condition feedback was unrelated to the actual estimate. The performance findings indicated that in the experimental condition, participants tended to adjust the new interval in the direction indicated by the feedback. In the control condition, however, the adjustments were largely unrelated to the information provided by the feedback. Heart rate slowed to feedback stimuli indicating that the estimate was outside the acceptable range. Surprisingly, cardiac slowing did not discriminate between experimental and control conditions. This finding seems to suggest that heart rate is sensitive to the valence rather than the information provided by the feedback. This finding is discussed vis-à-vis current neuroimaging and psychophysiological studies of performance monitoring.

Keywords: Heart rate; Performance feedback; Time production

* Corresponding author. Tel.: +31-43-3884097; fax: +31-43-3884092.
E-mail address: f.vanderveen@np.unimaas.nl (F.M. van der Veen).

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1. Introduction

The ability to adapt to a constantly changing environment is an important aspect of successful behavior. Adaptive behavior is only possible when the consequences of behavior can be evaluated. This evaluation depends on fast and flexible performance monitoring yielding important input to both motivational and cognitive systems. Performance monitoring and error processing have received much attention following the discovery of a negative ERP component (Error Related Negativity; ERN) following an erroneous response (Falkenstein et al., 1991; Gehring et al., 1992). The ERN peaks shortly after the error and appears to reflect the detection of the error rather than the inhibition or correction of the erroneous response (Falkenstein et al., 2000). Carter et al. (1998) argued on the basis of results of an fMRI experiment that the ERN might not be exclusively related to error detection. They found that the anterior cingulate cortex (ACC), which is thought to be the critical structure involved in generating the ERN (Carter et al., 1998; Dehaene et al., 1994; Kiehl et al., 2000), was not only active in situations where errors occurred, but also in situations in which errors *might* occur (see also Vidal et al., 2000). This finding seems to suggest that the ACC is implicated in the more general process of monitoring of ongoing behavior.

Evidence supporting a broader interpretation of the ERN was presented in a study which showed that the ERN can also be found in a paradigm in which the error is not directly detected, but external information tells the participant that an error was committed (Miltner et al., 1997). Miltner et al. used a time production task in which participants had to generate 1-s intervals by pressing a key to a cue with a 1-s delay. The key press initiated positive feedback when the interval was about 1 s, and negative feedback when its duration was either too long or too short depending on a dynamically adjusted criterion. The criterion was dynamically adjusted to keep error proportions at a fixed level throughout the task. It was found that that negative feedback was followed by an additional negative ERP component, which generally had the same properties as the ERN. Negative feedback was followed by a negative ERP component that, in virtually all respects, behaved like the typical ERN. This 'ERN' to feedback stimuli was interpreted to at least partly reflect the same neural process as involved in error detection (Miltner et al., 1997). However, in contrast to the ERN to errors (Gehring et al., 1992), the amplitude of the negative potential on trial n was not related to performance on trial $n + 1$. In this regard, this potential appears to be unrelated to remedial action.

A recent study by Somsen et al. (2000) showed that in addition to cortical changes, performance monitoring is also accompanied by immediate changes in HR. These investigators examined HR changes to feedback stimuli following responses on the Wisconsin Card Sorting Test. In this task, participants were instructed to match the geometrical shape(s) on a target card, which can differ with respect to the dimensions, number, shape and color, to one of four standard cards. In the computerized version used by Somsen et al., all cards were presented on a screen and after each sort trial participants received feedback about their performance. The sorting rule was changed every 10 cards and participants had to infer the rule by examining the information provided by the feedback signals. Somsen et al. showed that the cardiac response to negative and positive feedback signals differed. That is, both negative and positive feedback signals evoked cardiac slowing, but this decelerative response was larger for negative feedback stimuli. The size of the cardiac deceleration did not only depend on the valence of the stimulus, but also on the relevance of the feedback stimulus. After a rule change, participants needed to infer the new sorting rule on the basis of the feedback provided to them. Thus, feedback is highly relevant during the rule-inference phases of the task. But during the rule-application phase of the task, when the rule is known, the feedback is highly predictable and thus considerably less relevant. Somsen et al. observed that HR slowing to negative feedback was more pronounced during rule-inference phases relative to rule-application phases of the task. Somsen et al. interpreted this finding as an error-related deceleration, and suggested that both information value (i.e. whether or not feedback provided useful information) and mismatch properties (i.e. whether or not given and expected feedback matched) of the feedback signal were important factors in determining the amount of cardiac deceleration. Furthermore, they assumed a functional resemblance to ERN, which might be related remedial action (e.g. Gehring et al., 1992). A relation to remedial action has also been suggested in recent studies on cardiac responses to errors (Hajcak et al., in press; Van Boxtel et al., submitted).

The major aim of the current study was to further assess cardiac responses to feedback stimuli. More specifically, the study was designed to examine the effects of information value and the purported relation with remedial action. This was done by adopting and extending the Miltner et al. (1997) time production paradigm. As in the Miltner et al.'s study, participants were asked to produce 1-s intervals, and they received positive or negative feedback depending on the duration of the interval that was generated. For the present purpose, three changes were made to the Miltner et al., paradigm. First, monetary reward and punishment were attached to positive and negative feedback, respectively. Second, negative feedback communicated that the generated interval was either too short or too long. Finally, participants received a yoked-control condition, in which they received the series of feedback signals, that was presented in the preceding experimental condition. This design allowed us to address the following questions:

1. Do negative feedback signals elicit HR slowing? Under the hypothesis that HR changes to feedback stimuli are controlled by both the information value and the mismatch properties of these stimuli (Somsen et al., 2000), HR should differentiate between positive and negative feedback in the experimental condition but not in the yoked condition. The information provided by feedback is of no use in the latter condition and both positive and negative feedback have equivalent mismatch properties. It should be noted that this only holds if, during the course of task performance, the participant acquires an understanding that the feedback is non-informative, which can be tested by examining performance on trials following negative feedback.
2. Does HR reflect remedial action? The differential information provided by negative feedback ('too long' versus 'too short') allowed us to examine whether participants used the information provided by the feedback to adjust the next interval production. That is, we expected them to generate a shorter interval following 'too long' feedback and a longer interval following 'too short' feedback. Cardiac deceleration has been related to the inhibition of ongoing representations of action (Jennings and van der Molen, 2002). Somsen et al. (2000) observed such heightened deceleration after feedback suggesting that the current task representation for the WCST was in error. We then suggest that deceleration after negative feedback will indicate a transient inhibition reflecting a reorganization of the participants' interval estimation strategy. So, HR slowing to

negative feedback should be more pronounced on trials followed by correct interval adjustments relative to incorrect or failed adjustments. If, on the other hand, the cardiac response to feedback reflects the same process as the negative deflection described by Miltner et al. (1997), the amount of slowing should not predict remedial action.

2. Methods

2.1. Participants

Twenty participants (13 female, 7 male) participated in the experiment. The average age of the participants was 21.6 years (varying between 18 and 30). All participants were right-handed, healthy and screened for major health problems. Participants were paid a fixed amount of money and received student credit points for their voluntary participation. One participant who stopped performing in one of the task conditions was excluded from the participant sample.

2.2. Stimuli

The stimulus sequence consisted of a visual cue and a feedback stimulus. Participants were instructed to generate a 1-s interval, starting after the onset of the cue. Participants had to push a button on the keyboard with the index finger of their right hand whenever they thought that a 1-s interval had passed. The cue was an exclamation mark which remained visible for 200 ms. Exactly 1000 ms after the response, participants received feedback, which remained on the screen for 1000 ms. The feedback stimulus was either a plus (+) indicating that the interval was too long, a minus (−) indicating that the interval was too short, or a square (■) indicating that the interval had an appropriate duration. A time window surrounding the 1-s mark defined appropriate intervals. The next cue was presented 800 ms after offset of the feedback stimulus.

There were two conditions, in which the stimulus sequence and time estimation instruction were exactly the same. The first, experimental condition was based on the task that was used in the study of Miltner et al. (1997). In this task, the time window for which the interval was deemed appropriate was dynamically adjusted to the performance of the participant. When the interval was either too long or too short, the time window was prolonged by 20 ms. This was done by starting the time window 10 ms earlier and delaying the end of the time window by 10 ms. When the interval was appropriate, i.e. within the current time window, the opposite procedure was used by shortening the time window for the next trial by 20 ms. At the beginning of the task, the time window was 1 s ± 100 ms. The dynamical adjustment procedure was derived from Miltner et al. (1997), so as to keep accuracy at a fixed level of 50%.

In the second, yoked-control condition, participants were provided with the feedback series obtained during the experimental condition. Thus, in yoked-control condition, the feedback could not be used by the participant to generate more precise intervals. But, as in the experimental condition, the feedback communicated monetary gain (positive feedback) or loss (negative feedback) to the participant (see instruction below).

2.3. Procedure and instruction

The participants were seated in a sound attenuated room in front of a computer screen at a distance of approximately 100 cm. Before the experiment started, the participants were attached to the measurement devices. A training consisting of 10 stimuli preceded the tasks. The order of the two conditions was fixed as the feedback file to be used in the yoked-control condition had to be derived from the immediately preceding experimental condition. The experiment lasted about 1 h with brief breaks after each task-block. Instructions emphasized accuracy of the production of the task interval. Four task-blocks consisting of 120 trials each were presented, i.e. first two blocks of the experimental condition, and second two blocks of the yoked-control condition. The feedback given in the first block of the experimental condition was also used as feedback in the first block of the yoked-control condition, and the feedback given in the second block of the experimental condition was used as feedback in the second block of the yoked-control condition. Monetary reward and punishment was attached to the feedback. Participants were told correct intervals were rewarded by a small monetary gain whereas incorrect intervals were punished by a small loss (no exact amounts were mentioned). Participants were not told which blocks provided informative or uninformative feedback. Participants were told that they could earn between 2 and 4 euro. Due to the fixed accuracy level, it was impossible to increase the number of correct responses, and therefore we decided beforehand that all participants would receive the same amount of money, namely 4 euro. On the basis of a total amount of about 240 correct and 240 incorrect responses, the amount of money awarded for one correct response is about 4 eurocents.

2.4. Recordings and data reduction

Four accuracy indices were derived from the participants' performance on the time production task. These indices were computed for time segments of 20 trials. A first measure was the mean interval duration, which provides an index of overall time production performance. The standard deviation of the estimation time in separate 20 trial segments was as an estimate of within-subjects variability of performance. The width of the time window for which the interval was deemed appropriate served as an additional performance index. Interval adjustments were used as fourth performance index. Given that participants actually use the information provided by the feedback, 'too long' feedback should be followed by a shorter interval whereas 'too short' feedback should be followed by a longer interval. Note that for this performance index, the focus is not on the exact interval following negative feedback. It is only the direction of change that counts.

The ECG was derived from pre-cordial leads and sampled at 500 Hz. The *R*-peak occurrence times were detected with an accuracy of 2 ms and stored off-line. The series of *R*-peaks was checked for artifacts and corrected when necessary. Seven inter-beat intervals (IBIs) were selected around the presentation of the feedback stimulus; i.e. the concurrent IBI (i.e. IBI0), the three IBIs preceding the feedback stimulus (i.e. IBIs -3, -2, and -1), and the three IBIs following the feedback stimulus (i.e. IBIs 1, 2, and 3). These IBIs were referenced to the fourth IBI preceding feedback stimulus onset (IBI -4). We tested this reference interval and found that it did not differ between conditions and stimulus types.

2.5. Statistical analysis

Performance and cardiac responses were statistically evaluated with a repeated-measures ANOVA. Results of these analyses were corrected by the Greenhouse and Geisser procedure (Greenhouse and Geisser, 1959), where appropriate, and in these cases the ε-corrected P values are reported along with the original degrees of freedom. For all analyses, a difference was considered statistically significant when the P value was equal or less than 0.05. All performance measures and cardiac responses were tested separately. Mean estimation time and percentage correct adjustments were tested in a design with type of feedback (two levels; negative versus positive) and information value (two levels; informative versus uninformative) as within-subjects factors. Width of the estimation interval was only tested for the informative condition, and compared to the starting value (900–1100 ms: 200 ms). Both conditions were divided in 12 segments consisting of 20 trials each. These segments were used for the within-subjects factor time-on-task (12 levels), which was used for the tests of all performance measures.

The three IBIs surrounding the feedback stimulus were tested using a design with sequential IBI (three levels; preceding IBI1 versus concurrent IBI0 versus subsequent IBI1), type of feedback, information value and time-on-task as within-subjects factors. Follow-up analyses (ANOVA) were performed for significant interactions.

3. Results

3.1. Performance

The time production task was designed to produce an equal amount of positive and negative feedback stimuli, and this worked very well (49% positive versus 51% negative). Mean estimation time and the average standard deviation of estimation time are presented in Fig. 1. As can be seen in Fig. 1, standard errors of the mean estimation time were considerably higher in the yoked-control condition as compared to the informative condition. This suggests a higher between-subjects variability and, furthermore, that participants responded differently to feedback in the yoked-control condition. We tested this by computing the absolute difference between mean estimation time and the target of 1 s, and found that in the yoked-control condition this difference was significantly higher (152 ms versus 49 ms; $t = 3.1$, $P < 0.01$). The statistical test of mean estimation time itself showed that this measure did not discriminate between the experimental and yoked-control conditions, $F(1, 18) = 0.4$, $P =$ n.s., and effects of time-on-task were also not significant, $F(11, 198) = 1.7$, $P =$ n.s., $\varepsilon = 0.64$. The average standard deviation of estimation time did not change as a function of condition, but did change as a function of time-on-task, $F(11, 198) = 8.2$, $P < 0.001$, $\varepsilon = 0.44$. Follow-up analyses showed that the linear trend was not significant, $F(1, 18) = 3.9$, $P =$ n.s., but both the quadratic, $F(1, 18) = 8.2$, $P < 0.05$, and the cubic trend, $F(1, 18) = 48.8$, $P < 0.001$, were significant. The quadratic trend can be explained by an inverted U-shaped trend with lower standard deviations at the beginning and the end, and higher standard deviations in the middle part of the tasks. The cubic trend can be explained by similar inverted U-shape trends in the two separate

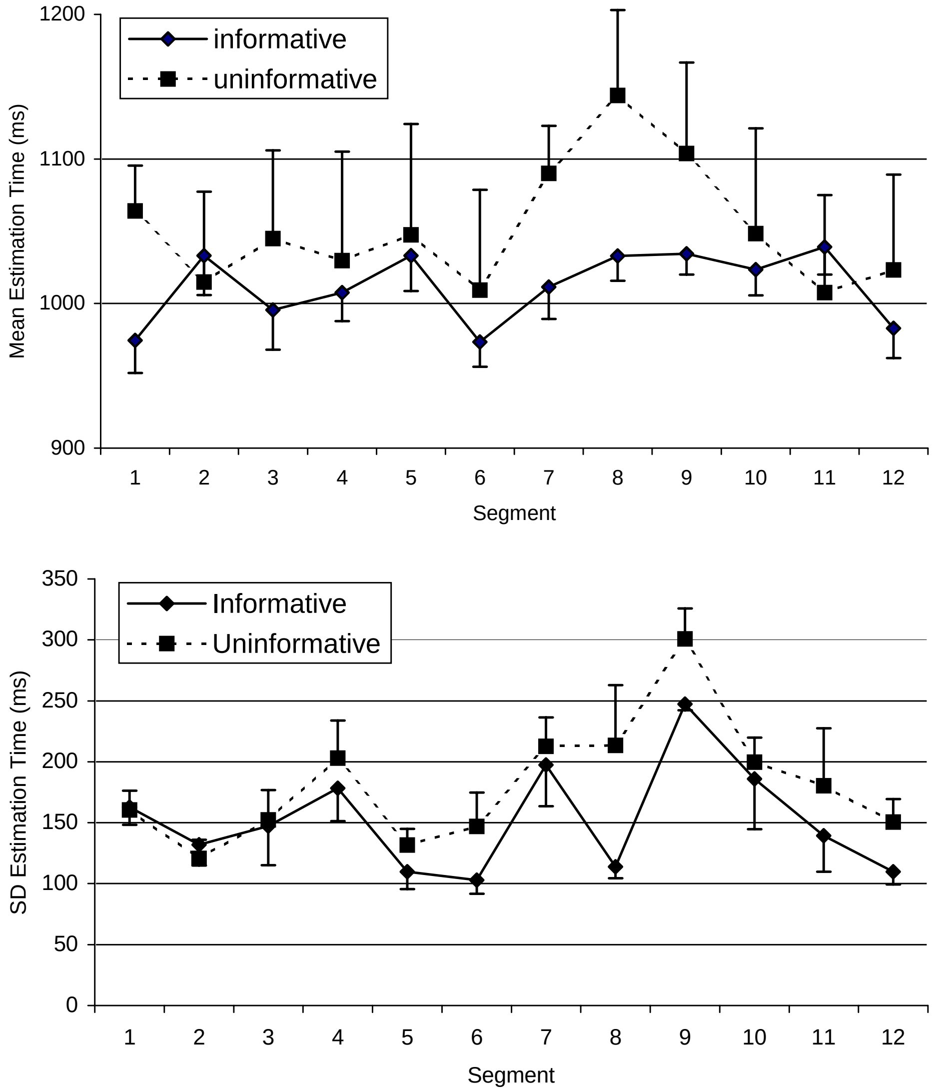

Fig. 1. Mean (top panel) and standard deviation (bottom panel) of estimation time in the informative and uninformative condition as a function of task segment (20 stimuli).

task-blocks. There was no significant interaction between time-on-task and information value, $F(11, 198) = 1.1$, $P =$ n.s., $\varepsilon = 0.448$.

The width of the time window, for which the interval was deemed appropriate, was dynamically adjusted and provides an additional index for evaluation performance in the experimental condition. As can be seen in Fig. 2, the width of the interval did not significantly change as a function of time-on-task, $F(11, 198) = 1.5$, $P =$ n.s., $\varepsilon = 0.75$, suggesting that participants failed to fine-tune their time productions.

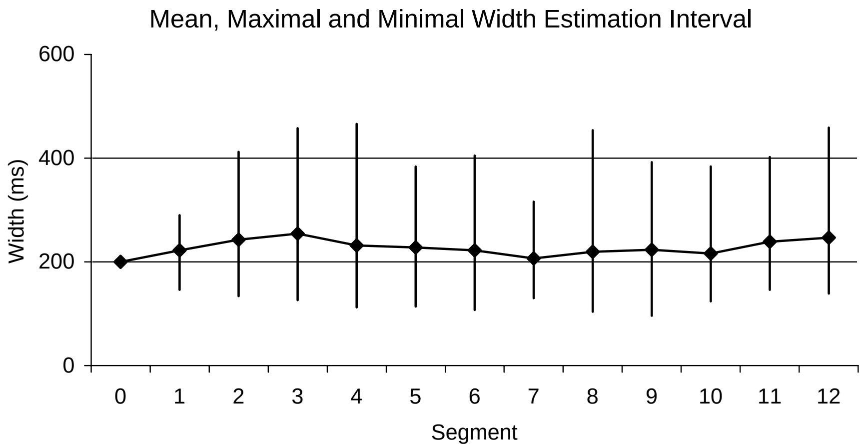

Fig. 2. Average, maximal and minimal width of the interval in which estimations were counted as correct in the informative condition as a function of task segment (20 stimuli).

Correct adjustments following negative feedback are plotted in Fig. 3 for both the experimental and yoked-control conditions. The proportion of correct adjustments was higher in the experimental condition relative to the yoked-control condition (82% versus 59%; $F(1, 18) = 184.3$, $P < 0.001$). Correct adjustments did not vary as a function of time-on-task, $F(11, 198) = 1.8$, $P =$ n.s., $\varepsilon = 0.62$. The number of correct adjustments in the yoked-control condition differed significantly from chance level (50%), $t = 5.3$, $P < 0.0005$.

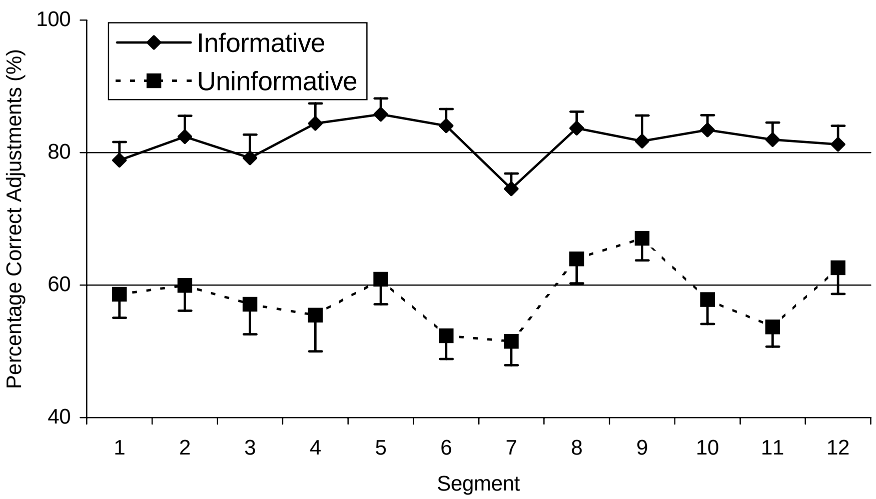

Fig. 3. Percentage correct estimation adjustments in the informative and uninformative condition as a function of task segment (20 stimuli).

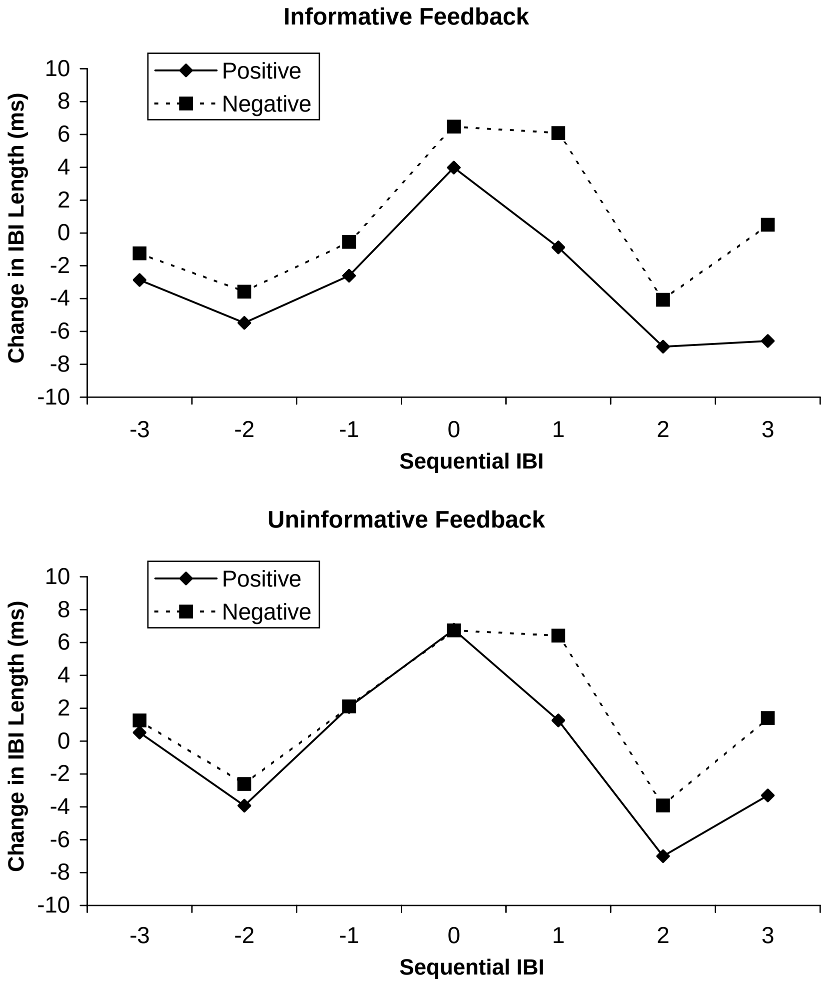

Fig. 4. Inter-beat intervals surrounding the onset of positive and negative feedback stimuli in the informative and the uninformative condition. IBI0 is the IBI concurrent with the onset of the feedback signal.

3.2. Heart rate

The three IBIs surrounding the feedback stimulus were used to examine whether positive or negative feedback stimuli evoked different cardiac responses. Furthermore, in a separate analysis we examined whether possible differences depended on the information value of the feedback stimulus, and time-on-task. Cardiac responses to negative and positive feedback signals are shown in Fig. 4 for both conditions. Statistical analysis revealed a significant interaction between the effects of feedback and sequential IBI, $F(2, 36) = 5.0$, $P < 0.05$, $\varepsilon = 0.75$. Follow-up analyses showed that the length of IBI1 was significantly longer for negative compared to positive feedback stimuli, whereas the IBI1 and IBI0 did not differ between feedback type. Importantly, the feedback effect on IBI length did not significantly discriminate between the experimental and yoked-control conditions $F(2, 36) = 0.03$, $P =$ n.s., $\varepsilon = 0.89$ and did not vary as a function of time-on-task, $F(2, 36) = 1.8$, $P =$ n.s., $\varepsilon = 0.86$.

Similar analyses were performed on the three IBIs surrounding the cue prompting participants to generate the required interval. For these analyses, the concurrent interval (IBI0) is the interval in which the cue falls. The three IBIs surrounding the cue were not sensitive to the type of feedback following the cue and response (feedback × sequential IBI, $F(2, 36) = 1.14$, $P =$ n.s., $\varepsilon = 0.64$) indicating that the IBIs surrounding the feedback stimulus reflect the cardiac response to the feedback stimulus rather than the processing preceding the feedback stimulus.

Participants differed considerably with respect to their performance in the yoked-control condition, as is evident from the large standard errors in mean interval duration plotted in Fig. 1. Some participants generated intervals that were quite discrepant from the target interval, whereas others performed almost equally well in the experimental and yoked-control conditions. Thus, the above analyses were repeated with group (median split on the basis of mean interval duration) as an additional factor. These analyses failed to show significant group effects (group × feedback × sequential IBI, $F(2, 34) = 0.3$, $P =$ n.s., $\varepsilon = 0.75$) indicating that the feedback effects on the IBI response do not depend on individual differences in performance.

Finally, it was examined whether the HR response was sensitive to remedial action by comparing negative feedback stimuli that were either followed by correct or incorrect adjustments in the informative condition. Type of adjustment (two levels) was used as a within-subjects factor in a test with sequential IBI as an additional factor. On average 98 correct and 22 incorrect trials entered the analysis, and the results of this analysis are shown in Fig. 5. This analysis revealed a significant interaction between type of adjustment and

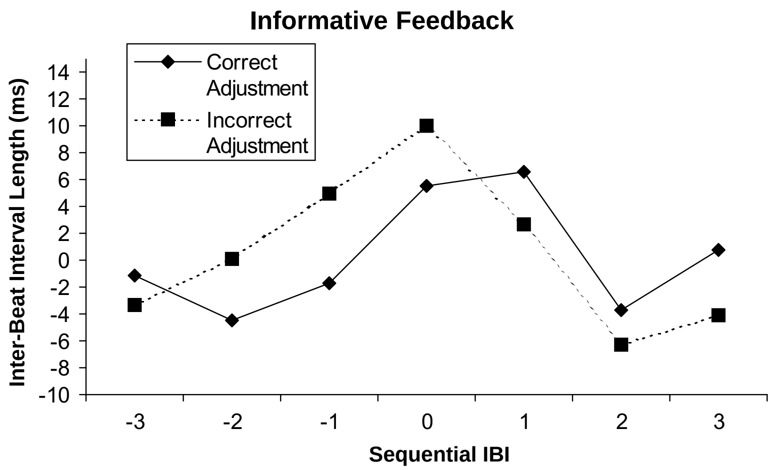

Fig. 5. Inter-beat intervals surrounding the onset of negative feedback stimuli in the informative condition, which are either followed by correct or incorrect behavioral adjustments (see text for details).

sequential IBI, $F(2, 36) = 3.3$, $P < 0.005$, $\varepsilon = 0.80$, which indicates that cardiac responses to feedback appear indicative of the initiation of an adjustment process which altered performance on the next trial. Post hoc analyses revealed close to significant different trends for the trials followed by correct and incorrect adjustments. IBIs surrounding trials followed by incorrect adjustment showed a quadratic trend, $F(1, 18) = 3.8$, $P < 0.1$, whereas IBIs surrounding trials followed by correct adjustments showed a linear trend, $F(1, 18) = 3.2$, $P < 0.1$. This difference in trends can be explained by prolonged deceleration in trials followed by correct adjustment (linear trend) and aborted deceleration in trials followed by incorrect adjustment (quadratic trend).

4. Discussion

The participants in the present study performed a time production task derived from Miltner et al. (1997) in which a cue prompted them to generate a 1-s interval. Participants performed the time production task under two conditions; first under the experimental condition and then under the yoked-control condition in which they received the series of feedback stimuli that was generated in the preceding condition. It was predicted that in the experimental condition participants would respond to negative feedback by adjusting the immediately subsequent interval in the direction indicated by the feedback (i.e. a shorter interval when the preceding interval was too long and a longer interval when it was too short). Indeed, the current findings indicated that correct adjustments were made more frequently in the experimental condition compared to the yoked-control condition in which they received uninformative feedback. The only performance measure that varied as a function of time-on-task was standard deviation of estimation time. The linear trend, however, was not significant and this effect did not interact with task condition. More informative measures like mean estimation time and percentage correct adjustments did, however, not change as a function of time-on-task. The overall pattern of findings suggests that, although participants used the feedback information provided to them in the experimental condition, they failed to increase precision during task performance. Increased precision in this case does not mean a higher percentage of correct estimations (this percentage was more or less fixed), but a narrower width of the estimation interval, indicating estimations closer to 1 s. Standard errors in mean interval duration were larger for the yoked-control condition relative to the experimental condition providing another indication that participants responded differently to the informative versus uninformative feedback.

The primary goal of the present study was to examine the effects of feedback on the concurrent HR response and to assess whether the cardiac response is sensitive to the interval information provided by the feedback. The current results showed a cardiac response that, most likely, consists of three separate components. The first component refers to a decelerative trend that can be observed to precede voluntary key press responses (e.g. Lacey and Lacey, 1974). The second component consists of added deceleration associated with the anticipation of the feedback stimulus (e.g. Damen and Brunia, 1987). The third component is related to the processing of the feedback signal and consists of a delay in acceleratory recovery associated with negative feedback relative to the cardiac response that can be observed for positive feedback (Somsen et al., 2000).

In the present study, the component of major interest is the cardiac slowing associated with negative feedback. This finding is consistent with the results reported previously by Somsen et al. (2000) for participants performing a computerized Wisconsin Card Sorting Test. The heart rate slowing to negative feedback discriminated between trials followed by correct performance adjustments and trials on which the participants failed again to generate the required interval. This finding suggests that heart rate reflects a mechanism implicated in remedial action. This is in accordance with recent studies (Hajcak et al., in press; Van Boxtel et al., submitted) which have reported cardiac slowing following response errors, and suggested that this error-related cardiac slowing is related to remedial action.

In the Somsen et al.'s (2000) study, HR slowing to negative feedback was most clearly seen following a non-signaled change in the sorting rule. HR slowing was observed to be considerably less pronounced to negative feedback that might occur when participants made an error while applying a sorting rule that was known to them. Somsen et al. interpreted these findings in terms of a combination of both the information value and mismatch properties of the feedback signal. Following this interpretation, HR will show a decelerative trend whenever a mismatch occurs between the information provided by the feedback stimulus and the participant's expectation derived from their performance on the task. However, this interpretation fails to provide a convincing account of the current findings because the HR slowing to negative feedback did not discriminate between the experimental and yoked-control conditions. In the yoked-control condition, there was only a very weak relation between task performance and the fake information provided by the feedback—the percentage of correct adjustments was just above chance level.[1] Thus, the participants must have acquired at least some understanding that the feedback did not help them to improve their performance, although we have no subjective reports verifying this. This should reduce the difference in cardiac response to positive and negative feedback, but it did not. This finding seems to make an interpretation in terms of mismatch properties and information value less attractive.

An alternative explanation, derived from Fowles (1988), suggests that heart rate is sensitive to the valence communicated by the feedback signal (reward versus punishment) rather than the performance information provided to the participant (right versus wrong). Fowles' model assumes that HR accelerates to feedback signaling reward and decelerates to feedback signaling punishment or non-reward. Fowles based his model on the work of Gray (e.g. Gray, 1975) who distinguished between a reward system, coined the Behavioral Activation System (BAS), that is involved in reward-triggered behavior and active avoidance, and a

[1] An anonymous reviewer suggested that feedback in the yoked-control condition may have been somewhat informative due to the fact that participants have a tendency to give more 'too slow' responses as compared to 'too fast' responses. Due to the fact that we have used the feedback of the 'informative' condition in the yoked-control condition, this might have led to an overrepresentation of 'too slow' feedback in this condition. In this way, the suggested tendency of more 'too slow' responses might have been accompanied by a higher percentage of 'too slow' feedback. This might have led to an increase to above chance level of the number of estimations accompanied by compatible feedback. We tested this by computing the number of 'too slow' and 'too fast' responses, which did not differ (64.5 versus 56.3; $P = 0.447$). Furthermore, we computed the number of responses that were compatible (e.g. 'too fast' estimation followed by 'too fast' feedback) or incompatible (e.g. 'too fast' estimation followed by too slow feedback) with the following feedback. The number of compatible and incompatible feedback stimuli did not differ significantly (63.4 versus 57.8; $P = 0.266$). These findings led to the conclusion that feedback appeared to be truly uninformative in the yoked-control condition.

punishment system, coined the Behavioral Inhibition System (BIS), that is involved in the inhibition of planned, or ongoing behavior when information arrives that signals punishment or non-reward. Fowles extended this model to incorporate autonomic responses, and he claimed that BAS activation is associated with increased HR levels whereas BIS activation is associated with an increase in electrodermal activity. There is a modest amount of evidence supporting this model. Clements and Turpin (1995), for instance, observed a relative HR increase to positive feedback in a difficult task, but not in an easy task. Iaboni et al. (1997) confirmed the relation between BAS and HR, and BIS and electrodermal activity in children.

The current finding that HR slowed to negative feedback signals in both the experimental and yoked-control conditions is compatible with an interpretation in terms of valence (see also Clements and Turpin, 1995). This interpretation assumes that participants continued to process the feedback provided to them in the yoked-control condition, even when this feedback stimulus did not help them to improve their time production performance. They continued to process the feedback because the valence of the feedback was important to them (in terms of gaining versus loosing money). This interpretation receives additional support from the consistent lack of time-on-task effects. Moreover, in recent studies, it has been suggested that at least parts of the cortical responses to feedback and errors might by related to the affective evaluation of the stimulus (e.g. Gehring and Willoughby, 2002; Luu et al., 2000, 2003). The data of the current study suggest that the cardiac response might be especially sensitive to this affective evaluation.

At this point, it could be argued that HR did not respond to the feedback signal per se but rather to the outcome of an internal action monitor. The performance results suggested that the time production task is very difficult to perform, and thus participants might have failed to notice a difference between the experimental and yoked-control conditions. Under the hypotheses that the internal action monitor operated during both conditions, it can then be predicted that, whenever the action monitor notices a difference between the required 1-s interval and the interval that has been actually generated, its output triggers a slowing of heart rate.[2] This interpretation is less likely for several reasons. First, the current findings suggested that the cardiac response was time-locked to the feedback signal rather than the key press terminating the time interval. Second, and more importantly, this interpretation fails to provide a convincing account of the yoked-control data. In the experimental condition, the output of the alleged internal action monitor is, at least on most trials, similar to the information provided by the feedback stimulus. In the yoked-control condition, however, there is no systematic relation between the output of the internal action monitor and the information of

[2] An anonymous reviewer suggested the possibility to us that participants might have relied on an internal action monitor rather than processing the information provided by the feedback. We pursued this issue by performing some additional analyses. More specifically, we performed a median split on the difference between the interval required and the interval that was actually generated. This analysis revealed that participants were less likely to adjust their intervals when the preceding interval was close to the required interval than when it was not (75% versus 88%; $F(1, 18) = 36.39$, $P < 0.001$). This finding is consistent with the notion that, to some extent, participants relied on an internal action monitor. This finding does not imply, however, that participants relied exclusively on their internal action monitor. This is clearly not the case, as intervals followed by negative feedback resulted more frequently in correct adjustment on the subsequent trial (76%) as compared to intervals followed by positive feedback (52%), $F(1, 18) = 175.51$, $P < 0.001$. This result indicates that participants did process the feedback and used the information provided by the feedback to adjust their performance.

the feedback stimulus. For the analyses, the data were sorted on the basis of negative versus positive feedback and when this categorization is not related to actual performance, as it is for the yoked-control condition, the differential output of the action monitor is distributed equally across the feedback categories. Consequently, one would then be led to predict that the heart rate changes associated with the feedback stimulus would not discriminate between positive and negative feedback. But the current findings showed otherwise.

In the current experiment, we chose to maximize the similarity between the feedback received in both conditions. This was done by recording the feedback received in the informative condition for every participant separately and presenting exactly the same feedback in the yoked-control (uninformative) condition. As a consequence of this procedure, the yoked-control condition was always presented as the second task, and this means that effects of task order might be a possible confound. Either a simple effect of time-on-task or a more subtle learning effect might have affected the current results. However, if this was the case, this should also be manifested in changes *within* the two conditions. Both our performance measures and cardiac responses provide evidence that is incompatible with an effect of task order. We did not find an effect of time-on-task. All measures did not change from one segment to the other. Apparently, both performance and cardiac responses were relatively stable over time. Given that time-on-task is not a significant influence within a task, there is little reason to believe that it is a factor between tasks. If participants would have learned the task in the informative feedback condition and then somehow 'unlearned' this task in the uninformative condition, this should have resulted in a change in performance measures and cardiac responses within both the informative and the uninformative condition. This was clearly not the case, which justifies the conclusion that task order was not an important influence in the current study.

In conclusion, the current findings contribute to the literature showing that heart rate is sensitive to performance feedback (e.g. Clements and Turpin, 1995; Fowles, 1988; Somsen et al., 2000). The finding that the cardiac response occurred, also when there was a very weak relation between performance and the information provided by the feedback, is most compatible with the Fowles' model. But it should be noted that the Fowles' model is based on tonic HR levels, whereas the current findings refer to phasic HR responses. Moreover, the Fowles' model predicts a relation between stimuli signaling positive reward and HR speeding rather than a relation between stimuli indicating punishment and HR slowing. Unfortunately, the current design, mixing positive and negative feedback within series of trials, precludes an assessment of the effects of feedback on tonic HR level. But the prediction of HR speeding in response to stimuli signaling reward is not incompatible with the current pattern of findings showing HR slowing in response to negative feedback relative to the cardiac response elicited by positive feedback. Obviously, HR speeding to positive feedback relative to the cardiac response to negative feedback is just another way of describing the same pattern of findings.

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