Human Performance Monitoring Research: What did we achieve, what remains to be solved?

Human performance monitoring has attracted the interest of many researchers. A steady increase in studies investigating the implementation of monitoring functions in the human brain and employing a number of different approaches could be observed over the recent years. A major part of this research is dedicated to error processing. This is not astonishing, as human life and development cannot be imagined to take place without errors. Errors themselves are often the basis of new strategies and learning. Anticipation, detection, correction, and avoidance of errors are major parts of goal-directed behavior. Investigation of these processes promises to reveal many insights in how humans can flexibly adjust to a continuously changing environment. Thus, the investigation of performance monitoring offers a way to understand the most complex psychological processes in human cognition. In addition, neuroimaging, electrophysiology and psychophysiology allow to investigate how these functions are implemented in the human brain.

In July, 2003, we had the great pleasure to organize the second conference exclusively dedicated to human performance monitoring research. Sixty contributions by most distinguished investigators as well as researchers at the beginning of their career demonstrated the remarkably fast development of the field. The outstanding presentations as well as fruitful and constructive discussions formed an enthusiastic atmosphere. We agree with numerous participants that both the Jena conference organized by Wolfgang Miltner and Mike Coles in 2000 and the recent Dortmund conference were highly successful and should be the starting point of a series of meetings dedicated to performance monitoring research.

This volume is intended to reflect the current state of performance monitoring research. It contains peer-reviewed original research contributions and overview papers from researchers who took part in the conference.
It addresses most questions discussed on the conference in July, 2003. In the first chapter, contributions on the event-related potential correlates of error processing, the error negativity (Ne) or error-related negativity (ERN) are integrated. Chapter two addresses the hemodynamic correlates of error processing as well as conflict monitoring. The third chapter comprises papers connecting performance monitoring to related cognitive processes, such as decision making, uncertainty monitoring, and affect. In addition, papers in this chapter discuss the different theories of performance monitoring. Chapter four is dedicated to response inhibition, a process which is often involved when errors are detected or response conflicts occur. The specific ERP responses to feedback and observed errors are discussed in chapter five. Chapter six sheds light on the psychophysiological responses accompanying performance monitoring processes. The consequences of errors, such as corrective behavior and learning, are discussed in chapter seven. Chapters eight and nine address the effect of state, trait, and developmental factors as well as pathological changes on performance monitoring. Finally, important methodological issues are discussed in chapter ten.

A major means in performance monitoring research is to investigate the correlates of error processing. The best-studied candidates are the ERN/Ne in the electrophysiological domain and an increased hemodynamic signal from the anterior cingulate cortex (ACC) in functional magnetic resonance imaging (fMRI). As depicted in Figure 1, we use two main theoretical approaches in addressing the question what the measured phenomena can tell us about performance monitoring. As evident on the conference and in this volume, the number of combined studies being based on psychological theories as well as functional neuroanatomy is increasing steadily. In addition,

evidence from pharmacology and pathophysiology are being integrated. The main goal, a neurally plausible computational model of performance monitoring and ACC function seems to get closer.

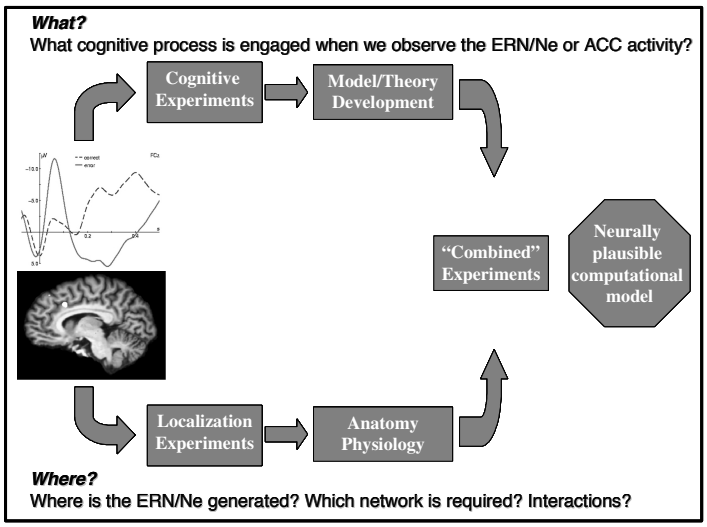

Figure 1.
Research approaches in the investigation of ACC function and the ERN/Ne (after Coles, 2003). Cognitive as well as localization studies, combined with state manipulations, pharmacological treatment and experiments in patients need to be combined and integrated. A promising approach is the development of neurally plausible computational models to formulate testable hypotheses.

Despite the fast development of performance monitoring research a number of important questions remains to be resolved. Based on Mike Coles' brilliant final discussion in Dortmund, we present main issues that need to be addressed in future research.

Let us first focus on current issues in ERP research of performance monitoring.

1. How do we measure the ERN/Ne? A number of different approaches have been used; and not all are equally suitable for all questions. Clarification is needed with respect to the reference electrodes, whether to use difference wave or constituent waves, how to measure amplitudes (trough-to-peak, base-to-peak, what base?). Furthermore, the advantages and disadvantages of Laplacian derivates must be taken into account. Likewise it needs to be specified what we can learn from the promising time-frequency decomposition method.
2. How can we be sure that we measure the ERN/Ne? How do we deal with component overlap and contaminations with stimulus-related ERPs? Some of these issues are discussed in Chapter ten. No final consensus has been found so far with respect to the value of ICA and PCA for this issue. In any case it seems helpful to look at response-locked as well as stimulus-locked ERPs and to investigate a number of response time bins.
3. How many instances of the component are there? Are there equivalents to the incorrect-response-related negativity, i.e., the classical ERN/Ne? Candidates would be the feedback-related negativity, the N2, the correct-related negativity, and the observed incorrect-response-related negativity (see Chapters 1, 3, 4, 5). What are the criteria for equivalence? On one hand one could argue that same scalp topography and a generation in the same structure is the best criterion. On the other hand, however, one could assume similar processes taking place in different brain structures. In any case, if equivalence is assumed, a theory must account for all equivalent instances.
4. What is the relationship between the ERN/Ne and remedial actions? At first, one needs to define remedial actions. Recent research suggests that not all immediate corrections are in fact intended as such but may rather be delayed correct responses independent of error detection (Rabbitt, 2002; Fiehler et al., 2003, submitted). Similarly, the issue of post-error adjustments as well as sequential dependency effects in conflict tasks is not fully resolved (cf., e.g., for the ongoing debate on the "Gratton effect" to Leuthold, this volume; Mayr et al., 2003; Botvinick et al., in press; Ullsperger et al., submitted).

When we look at fMRI studies, we face similar questions.

1. Does activation of the ACC always result from the same process? The ACC has been reported to be activated in a number of conditions which seem to be related neither to errors nor to response conflict. Time-course analyses of the fMRI signal revealed that the ACC is also engaged in correct responses. It seems therefore unlikely that the ACC is dedicated exclusively to one process – be it error detection, response conflict monitoring, reinforcement learning, selection for action or pain processing.
2. What sub-areas of the ACC and the adjacent median wall are involved? Cytoarchitectonics as well as connectivity suggests a functional differentiation of these sub-areas.
3. What are the other players in the network? fMRI offers a good opportunity to investigate the involvement of other brain regions in performance monitoring.

A further issue to be solved is the integration of electrophysiological and hemodynamic data. The relationship between the ERN/Ne and the hemodynamic activity of the ACC is likely to be complex and non-linear.

These open questions offer a number of highly interesting ways to continue with performance monitoring research. We are convinced that research of the next years will yield many surprising findings which will help to revise and refine our current theories of performance monitoring. We think that a continuation of the performance monitoring conference tradition can act as an engine and catalyst by intensifying discussions, starting new collaborations, and creating new ideas.

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