COMPARISON PROCESSES IN MEMORY: PERFORMANCE INDICATORS AND SYNCHRONOUS BRAIN ACTIVITY

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ABSTRACT

A process-based, memory psychophysics with strong relations to cognitive psychology provides an important basis for deriving information concerning those cognitive operations underlying comparison processes in memory. Performance data alone are not sufficient for a full understanding of these comparison processes; instead, combinations of performance measures with appropriate neuroscience measures seem more useful. Because cognitive functions are based on parallel, distributed information processing, the concept of synchronous activity between certain cortical subsystems is of special importance. The potential advantages and problems with such an approach are discussed on the basis of experimental variations and results.

The approach of the *Psychology of Comparison* deals with fundamental mental operations in perception and cognition. What are current methods to get information about the cognitive operations underlying comparison processes in memory?

Memory Psychophysics (or Mnemophysics) is concerned with the functional relations between physical stimuli and their remembered responses (Algom, 1992). The solution to comparison problems is analyzed in both perception *and* memory. Mnemophysics aim at deriving psychophysical functions and identifying different and common subprocesses. To this end, experiments have been carried out to derive psychophysical functions for perception and memory for common sets of referent stimuli (Algom & Marks, 1989). Tasks involving the paired comparison of ordered stimuli are one of the main topics of investigation (for example Petrusic et al., 1998). In addition, cognitive-process models are developed which predict the symbolic distance effect, the semantic congruity effect and the end-point effect (Leth-Steensten & Marley, 1998). It can thus be concluded that the development of a process-based memory psychophysics with strong relations to cognitive psychology is a useful and interesting enterprise.

One aim in *Cognitive Psychology* is to identify basic components in memory and reasoning. In this case, basic components take the form of substantive *operations* and sequences of operations and may be considered together with the *mental effort* necessary for successful component operationalization (Klix, 1971). For solutions to memory-based comparison problems, working memory employs control processes to temporarily maintain and manipulate information. Information concerning these substantive components of memory-based, comparison processes requires variation of those relevant properties of the stimuli (and variation of relations between them), which cause change in the mental effort demanded by the control and online manipulation of to-be remembered information.

MENTAL EFFORT

There are some cognitive components of mental effort, which are especially important for memory-based, comparison processes. These include, the mental effort incurred by the temporary maintenance of previously learned (and inferred) information (the “working memory load”), the mental effort for online manipulation of information during memory comparison (the “information processing effort”) and the mental effort required for coordination of processes involved in the temporary maintenance and manipulation of information (the “coordination or control effort”). If task-relevant aspects of the to-be-remembered information are also activated, additional mental effort (“activation effort”) becomes necessary.

In our investigations we have investigated stimulus- and task-dependent changes in cognition. This procedure is in analogy to Fechner’s conception of outer psychophysics, which is concerned with stimulus-dependent changes in sensation (Fechner, 1860/1907). Our cognitive parameter is the mental effort by which the subject carries out a specific operation (or sequence of operations) during memory-based comparison. We have varied those properties of the stimuli (and the task) that *cause* changes in certain components of mental effort relevant for comparative information processing. This corresponds to the principal question of Kostić (2001) who posed the question of to *which* relevant stimulus properties our cognitive system is sensitive. Consequently, we have defined and varied appropriate independent variables with the requirement of *measuring* changes in mental effort. But which are the indicators for the construct of “mental effort”? Or in other words: “What are appropriate dependent variables that indicate changes in mental effort which is necessary for certain subprocesses in memory based comparison?”

INDEPENDENT AND DEPENDENT VARIABLES

In the following I would like to discuss independent and dependent variables for tasks involving the paired comparison of linear ordered stimuli.

Independent variables for causing changes in mental effort

Task difficulty can be operationalized by the symbolic distance (in ordinal units) of the two elements to be compared, and in addition by the position of a single element. Task difficulty also depends on the congruence of the polarity of the relation in the instructions and the polarity of the relation in the set of experimental stimuli. In linear-order problems, an operationalization of *task complexity* by the number of elements is appropriate, because there is only one relation and only one type of order. *Task practice* can be operationlized by the number of sessions in which subjects are required to solve ordering problems.

Dependent variables indicating changes in mental effort

External Indicators

On the basis of the “reaction time” and “rate of error” performance measures, interesting experimental results have been found and appropriate theoretical approaches have been developed to explain substantive representational and information-processing components during memory-based comparison. On these bases, experiments in psychophysics and cognitive psychology have been used to infer the rules of mental representation and information processing during comparison (e.g. Potts, 1975; Sommerfeld, 1994; Petrusic et al., 1998; Leth-Steensten & Marley, 1998; Krause, 2000). This protocol is similar to Fechner’s conception that the findings in outer psychophysics are one possible basis for inductive knowledge concerning the structures of inner psychophysics. However, performance data alone are not sufficient for a full understanding of comparison processes and lead to the question of which processes in the brain indicate changes in the mental effort for the process control during the temporary maintenance and manipulation of information? One promising way to answer the question for relevant processes in the brain is to examine activation in task-relevant cortical subsystems and look for synchronous activity between these subsystems.

Internal Indicators

Activation of cortical subsystems: On the basis of functional magnetic resonance imaging (fMRI) and positron emission tomography (PET), numerous neuroimaging studies have demonstrated a particular activation of prefrontal cortex during task conditions that engage working memory (e.g. Smith & Jonides, 1997). Braver et al. (1997) varied memory load and found a linear relationship between fMRI-activity in specific regions of prefrontal cortex and working memory load. Non-frontal activity was also found in bilateral posterior parietal cortex. Based upon these findings, it seems profitable to examine the functional couplings of frontal and parietal subsystems during the performance of tasks with differential difficulty or complexity and both before and subsequent to practice.

Synchronization of cortical subsystems: The synchronous activity of specific brain areas can be revealed by EEG coherence measures. (e.g. Schack et al., 1999). A number of experiments have shown high coherence between frontal and posterior brain areas when subjects were required to solve a working-memory task. In general, the Theta frequency band (4-7.5 Hz) seems to be of particular importance for the active maintenance of information (e.g. Petsche & Ettlinger, 1998; Sarnthein et al., 1998; Tesche & Karhu, 2000), and may be related to the theory of Lisman and Idiart (1995), which identifies Theta activity in the hippocampus with the short-term information retention. Changes in mental effort for control processes are indicated by changes in the coherence between specific frontal and parietal areas in parts of the Beta frequency band (ca. 13-30 Hz) (e.g. Petsche & Ettlinger, 1998), and of particular interest in this respect, the Beta1 frequency band (ca. 13-20 Hz) seems to be sensitive in comparison processes (e.g. Petsche & Ettlinger, 1998; Sommerfeld et al., 1999).

Are there potential benefits if psychophysical methods are supported by the, above-mentioned, neuroscience measures? Fechner's conception of an inner psychophysics refers to the relationship of sensations to the neural activity underlying them (Fechner, 1860; Klix, 1962; Scheerer, 1992). In analogy to this relationship, the psychophysical examination of memory processes searches for relations between cognition and the brain activity underlying them. In the modern conception of psychophysics, relations between the stimulus and the neural activity serve as an important bridge between outer and inner psychophysics (Ehrenstein & Ehrenstein, 1999). Thus, the concept of synchronous activity between certain brain regions seems to be of special importance because cognitive functions are based on a parallel and distributed information processing.

EXPERIMENTAL VARIATIONS AND RESULTS

Cognitive tasks

Subjects were required to compare relational information concerning pairs of elements with an artificially induced linear ordering learned and inferred in an initial learning situation (for example Potts, 1975, Sommerfeld, 1994; Petrusic et al., 1998; Leth-Steensten & Marley, 1998; Krause, 2000).

Data analysis

During task performance, EEG activity was recorded from the scalp at 19 electrode positions according to the international 10-20 system (Schack et al., 1999). Reaction time (RT), error rates and the absolute and percentage coherence duration were analyzed as functions of the task difficulty, task complexity and task practice. The absolute coherence duration is defined as the period of high coherence (larger than a defined threshold) during the RT interval. The percentage coherence duration is calculated as the absolute coherence duration divided by RT. In our experiments, we investigated the interregional coherence between frontal-electrode positions and parietal positions and the local coherence within frontal and parietal positions. The threshold is based on the histograms of the coherences in the different experimental conditions and was set for the interregional coherence duration to 0.65 and for the local coherence duration to 0.8. The EEG data were analyzed by means of an adaptive algorithm of fitting bivariate time-dependent ARMA models (Schack et al., 1999). These analyses were restricted to band coherences within the Theta frequency band (4-7.5 Hz) and the Beta1 frequency band (13-20 Hz). Only the correct-decision trials without EEG artifacts were examined. To determine the significant RT differences between experimental conditions, variance analyses were computed. The statistical analysis of the coherence-duration differences was carried out using the Kruskal-Wallis H test and the Mann-Whitney test or the Friedman test in combination with the test for contrasts within dependent samples (Lohse et al., 1986), respectively (significance level of 5 %).

Results

Performance measures and synchronous brain activity as functions of task difficulty and task complexity: Koehler et al. (2001) found both increases in RT and increases in (absolute and percentage) left hemispheric fronto-parietal coherence duration (CD), in the Beta1 frequency band, as functions of the *number of elements* in the linear order. This is in accordance with our assumptions that the mental effort for the coordination of temporarily maintained and online-manipulated information increases with set size and is indicated by an increase of specific fronto-parietal synchronization. In contrast to this, only RT increases with a decreasing *symbolic distance* in the linear order, while CD did not change significantly. This result could reflect the possibility that control effort for the coordination of temporarily maintained and online-manipulated information does not change significantly. The structural information that has to be maintained in working memory remains the same. Because of greater uncertainty with shorter distances, subjects have to carry out more (but not more difficult) fixation operations (Krause, 2000). In other words, they need more time, but not more control effort for the comparison. These conclusions bear some similarity to the results of Doerfler et al. (2001), who also showed that, for item memorization, left hemispheric fronto-parietal CDs in the Beta1 and Theta band increased with the number of elements of the linear order that have to be kept in mind.

Performance measures and synchronous brain activity as functions related to task practice: Simmel et al. (2001) found practice-dependent reductions in RTs and left-hemispheric, fronto-parietal Theta CD as well as locally increasing right fronto-parietal Beta1 CD followed by a locally strongly decreasing error rate. In the present investigation, we also analyzed the topological differences in *interregional* and *local* synchronization of frontal and parietal brain areas and the results of the RT in combination with left- and right-hemispheric absolute CDs in the Beta1 band for six subjects are given in Figure 1**.**

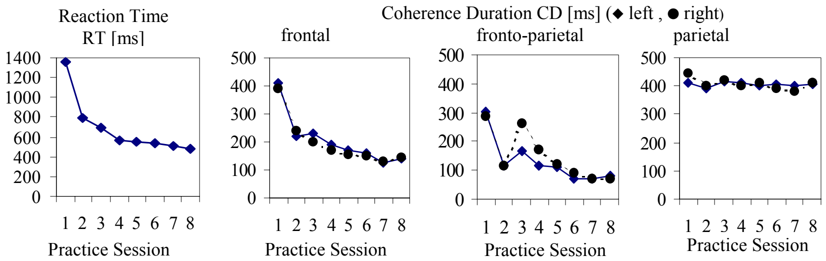

Figure 1. Graphs of the mean reaction time RT[ms] and the mean coherence duration CD[ms] at left- and right-hemispheric frontal (FzF3, FzF4), fronto-parietal (FzP3, FzP4) and parietal (PzP3, PzP4) positions within the Beta1 frequency band (13-20 Hz) as functions of the practice session, for six subjects.

In Figure 1, it can be seen that the practice-dependent, decreasing curves of the frontal CD are very similar to the RT functions. This appears to indicate that a practice-dependent reduction of mental effort as it relates to control processes, is accompanied by a reduction in the RT, together with a reduction of synchronization strength within frontal brain regions. There is no significant increase of CD during intervening periods as is found for the interregional right-hemispheric fronto-parietal CD. This form of fronto-parietal CD curve was also found by Sommerfeld and Krause (1998) during subject's comparisons of Garner patterns. The partial increase of fronto-parietal synchronization could represent the forgetting of relevant parts of information that then required reactivation and maintenance in working memory. This then raises the possibility that the reactivated information required some additional mental effort for maintenance and coordination, although it could also indicate that subjects are actively changing their task strategy. Further experiments are necessary to obtain more specific information regarding this issue. In contrast to the global decrease of frontal and fronto-parietal CDs, the CD within parietal regions remains globally constant. This could mean that, as performance becomes increasingly automated during the course of practice, processing becomes increasingly centered in parietal brain areas, while at the same time the central executive becomes increasingly detached from its function as task controller.

CONCLUSION

The present study highlights the potential benefits of neuroscience measures along with psychophysical performance indicators. Based on the different and common features of the coherence functions it becomes possible to reveal differences in the synchronous activity of certain brain regions as indicators of differences in mental effort for those control processes involved in the temporary maintenance and manipulation of information. In future research, these kind of experimental variations and results should be systematically combined with existing models about memory based comparison processes and approaches about oscillations in the brain.

Nevertheless, it should be borne in mind that, even when the neural and psychophysical responses exhibit the same time course, these functional similarities do not guarantee that they represent the same mechanisms (Uttal, 1996). Under such circumstances, if care is taken with the conceptual basis and the interpretation of the results, such investigations could serve as one span of the rapidly constructing bridge between outer and inner psychophysics.

REFERENCES

Algom, D. (Ed.) (1992) *Psychophysical Approaches to Cognition.* Amsterdam: North-Holland.
Algom, D. & Marks, L.E. (1989) Memory psychophysics for taste. *Bull. Psychonomic Society*, 27, 257-259.
Braver, T. S., Cohen, J. D., Nystrom, L. E., Jonides, J., Smith, E. E. & Noll, D. C. (1997) A parametric study of prefrontal cortex involvement in human working memory. *NeuroImage* 5, 49-62.
Doerfler, T., Simmel, A., Schleif, F.-M. & Sommerfeld, E. (2001) Complexity-dependent synchronization of brain subsystems during memorization (*this volume*).
Ehrenstein, W.H. & Ehrenstein, A. (1999) Psychophysical methods. In: Windhorst, U. & Johansson, H. (Eds.) *Modern Techniques in Neuroscience Research.* Berlin, Heidelberg: Springer, 1211-1241.
Fechner, G.Th. (1860/1907) *Elemente der Psychophysik.* Leipzig: Breitkopf und Haertel.
Klix, F. (1962) *Elementaranalysen zur Psychophysik der Raumwahrnehmung*. Berlin: DVW.
Klix, F. (1971) *Information und Verhalten*. Berlin: DVW.
Koehler, M., Buchta, K., Schleif, F.-M. & Sommerfeld, E. (2001) Synchronous activity of brain subsystems as a function of the number of items in memory based comparison of relational information (*this volume*).
Kostic, A. (2001) The effect of the amount of information on language processing (*this volume*).
Krause, W. (2000) *Denken und Gedaechtnis aus naturwissenschaftlicher Sicht*. Goettingen, Toronto: Hogrefe
Leth-Steensten, C. & Marley, A.A.J. (2000) A model of response time effects in symbolic comparison. *Psychological Review*, 107, 62-100.
Lisman, J.E. & Idiart, M.A. (1995) Short-Term Memories in Oszillatory Subcycles. *Science,* 267, 1512-1515.
Lohse, H., Ludwig, R. & Röhr, M. (1986) *Statistische Verfahren.* Berlin: Volk und Wissen.
Petrusic, W.M., Baranski, J.V. & Kennedy, R. (1998) Similarity comparisons with remembered and perceived magnitudes: Memory psychophysics and fundamental measurement. *Memory and Cognition*, 26, 1041-1055.
Petsche, H. & Ettlinger, S.C. (1998) EEG aspects of cognitive processes: A contribution to the Proteus-like nature of consciousness. *International Journal of Psychophysiology*, 33, 199-212.
Potts, G. R. (1975) Bringing order to cognitive structures. In: Restle, F., Shiffrin, R. M., Castellan, N. J., Lindman, H. R. & Pisoni, D. B. (Eds.) *Cognitive Theory*, vol. 1. New York: Wiley, 247-270.
Sarnthein, J., Petsche, H., Rappelsberger, P., Shaw, G.L. & von Stein, A. (1998) Synchronization between prefrontal and posterior association cortex during human working memory. *Proceedings of the National Academy of Sciences USA*, 95, 7092-7096.
Schack, B. , Grieszbach, G. & Krause, W. (1999) The sensitivity of instantaneous coherence for considering elementary comparison processing. Part I: The relationship between mental activities and instantaneous EEG coherence. *International Journal of Psychophysiology*, 31, 219-240.
Scheerer, E. (1992) Fechner's inner psychophysics: Its historical fate and present status. In: Geissler, H.-G., Link, S.W. & Townsend, J.T. (Eds.) *Cognition, Information Processing, and Psychophysics.* Erlbaum: Hillsdale NJ, 3-21.
Simmel, A., Doerfler, T., Schleif, F.-M. & Sommerfeld, E. (2001) An analysis of connections between internal and external learning process indicators using EEG coherence duration (*this volume*).
Smith, E. & Jonides, J. (1997) Working memory: A view from neuroimaging. *Cognitive Psychology*, 33,5-42.
Sommerfeld, E. (1994) *Kognitive Strukturen.* Münster, New York: Waxmann.
Sommerfeld, E. & Krause, W. (1998) The effect of practice in a working memory task on synchronization of specific brain areas. In: Grondin, S. & Lacouture, I. (Eds.) *Fechner Day 98.* Quebec, Canada: The International Society for Psychophysics, 355-360.
Sommerfeld, E., Krause, W., Schack, B., Markert, C., Pies, R. & Tietze, H. (1999) Zur Messung von Übungs- und Trainingserfolg auf der Grundlage von EEG-Parametern. *Zeitschrift für Pädagogische Psychologie*, 13(1/2), 60-73.
Tesche, C.D. & Karhu, J. (2000) Theta oscillations index human hippocampal activation during a working memory task. *Proceedings of the National Academy of Sciences USA*, 97, 919-924.
Uttal, W.R. (1996) Do bridges exist between psychophysics and neurophysiology? In: Masin, S. (Ed.) *Fechner Day 96.* Padua, Italy: The International Society for Psychophysics, 1-21.

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