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When intelligence loses its impact: neural efficiency during reasoning in a familiar area

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Abstract

Several studies have revealed that persons with a lower IQ show more cortical activity when solving intelligence-related tasks than more intelligent persons do. Such results are interpreted in terms of neural efficiency: the more intelligent a person is, the fewer mental resources have to be activated. In an experiment with 31 experienced taxi drivers of varying IQs (measured by Raven's advanced progressive matrices test), we investigated cortical activation by measuring the amount of event-related desynchronization in the electroencephalogram during a familiar task (thinking about routes to take in their city) and a novel task (memorizing routes of an artificial map). A comparison of participants with lower and higher IQs (median split) revealed higher cortical activation in the less intelligent group for the novel task, but not for the familiar task. These results suggest that long-term experience can compensate for lower intellectual ability, even at the level of cortical activation.

Keywords: Intelligence; Electroencephalogram; Event-related desynchronization; Neural efficiency; Expertise; Cortical activation; Knowledge

1. The neural efficiency hypothesis

The tremendous cognitive variability found in human beings is the result of differences in brain functioning as well as in the exploitation of learning opportunities provided by the environment. Many studies attempting to explore the neurophysiological correlates of psychometric intelligence have led to the development of the neural efficiency hypothesis, which postulates a more efficient use of brain resources in more intelligent people than in less intelligent people. Evidence for this hypothesis has been provided by different research approaches to the human brain. Haier et al. (1988, 1992b) used positron emission tomography to measure the glucose metabolism of subjects performing cognitive tasks and found that the brains of more intelligent persons consumed less glucose (or energy) than those of less intelligent ones. The results of studies using parameters of the electroencephalogram (EEG) as indicators for brain or cortical activation were also in line with the neural efficiency hypothesis (e.g. Jausovec, 1998, 2000;

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Neubauer et al., 1995, 2002; Vitouch et al., 1997). Neural efficiency was reflected in lower and more focused cortical activation, presumably restricted to those areas that are relevant for solving the cognitive tasks in question. Even in very simple tasks, where persons of different intelligence levels reach the same performance level, an impact of intelligence on cortical activation was observed (Neubauer and Fink, in press).

2. Intelligence and learning

In societies based on the division of labour, people are expected to specialize in different areas of expertise by selecting learning environments that allow them to perfect particular competencies through engaging in deliberate and continual training and practice (Ericsson et al., 1993). Frequent practice of certain tasks allows the underlying knowledge to be proceduralized and chunked and, as a consequence, to be accessed efficiently and flexibly when coping with familiar as well as with novel demands. Extraordinary memory performance with numbers (Ericsson and Chase, 1982) or chess positions (Chase and Simon, 1973) presupposes a hierarchically organized knowledge base built up through long-term practice with the aid of chunking strategies.

It is thoroughly plausible to expect intelligence to guide the selection of fields of specialization in a person's professional as well as private life and to impact on the exploitation of learning environments. Persons with a below-average IQ will hardly be able to cope with the demands of training programs in areas such as theoretical physics, even if they are credited with extra time. However, research on expertise also suggests that once an elaborate knowledge base in a specific domain is acquired, differences in intelligence no longer contribute to the explanation of achievement variance. Achieving expertise in an academic domain presupposes an IQ exceeding a certain threshold, but beyond this threshold, domain-specific knowledge has proved to be necessary—and indeed sufficient—for outstanding achievement (for an overview, see Schneider, 1993).

There are, of course, many areas in professional and private life where less intelligent persons can acquire expertise. Schneider et al. (1989) found a main effect of prior knowledge, but no effect of general intelligence, on achievement in recalling a text about soccer. Less intelligent experts did not differ from more intelligent experts, and they outperformed novices who were more intelligent than they were. Note that the study considered novices rather than laypersons. In contrast to laypersons, novices possess domain-specific knowledge in terms of rules and core concepts, but they differ from experts in their lack of practice. Longitudinal studies on school-related achievement suggest that learning outcomes are determined by prior knowledge rather than by intelligence. Preschool indicators of letter identification and phonological awareness were a better predictor of later performance in reading and writing than general intelligence was (Schneider and Näslund, 1999). Similar results were found for mathematics (Stern, 1994, 1999): it emerged that, even at elementary school level, prior knowledge could compensate for lower intelligence, but that higher intelligence could not compensate for prior knowledge. Differences in intelligence seem to come into play only if strategies acquired in specific areas of expertise have to be generalized to fit new demands (Schneider and Bjorklund, 1992; Schunn and Anderson, 1999).

3. Design and research question

Once an elaborate knowledge base has been developed in a particular area, intelligence no longer seems to affect the performance that can be achieved in this area. However, it is thoroughly plausible that intelligence affects cognitive activities beyond the performance level—the lower a person's IQ, the higher the cortical activation that may be necessary for this person to cope with the respective demand. Online registration of cortical activation during reasoning in an area of expertise assumed to be chosen by people of various levels of intelligence allows us to test this hypothesis. We studied the neural efficiency of experienced taxi drivers of varying IQs by presenting them with an expertise task based on familiar taxi routes and with a novel, intelligence-related task requiring them to memorize routes of an artificial map. If

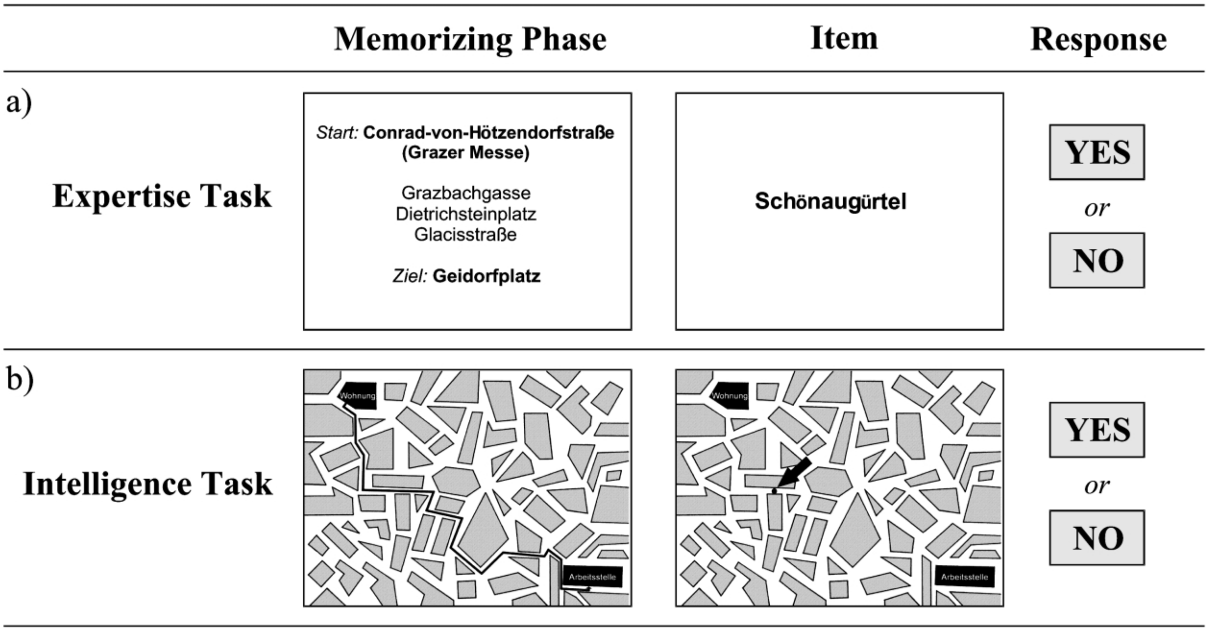

Fig. 1. (a) Expertise task. In the memorizing phase, routes were verbally presented and consisted of a starting point, an end point, and 3–5 street names determining the route to take. (b) Intelligence task. Routes were marked on a fictitious and abstract city map, covering the way from a point named 'Wohnung' (flat) to a point named 'Arbeitsstelle' (place of work). The marking point in the item above is set off with a black arrow.

people with lower and higher IQ differ in their cortical activation when processing the intelligence-related task but not when processing the expertise task, we may conclude that long-term, deliberate practice can compensate for lower intellectual ability, even at the level of neural efficiency.

4. Method

4.1. Participants

Thirty-one male taxi drivers with work experience in Graz, Austria participated in the study in exchange for financial remuneration. Participants' age ranged from 21 to 57 years ($M = 38.10$, S.D.$=$ 10.60), and the amount of work experience was between 7 months and 25 years ($M = 8.15$, S.D.$=$ 6.52). All participants were right-handed (as determined by self-report) and without any obvious signs of medical or psychological disorders.

4.2. Material

In a 2.5-h single session, participants were presented with paper–pencil intelligence and personality measures, and their neural efficiency during solving the computer-based intelligence and expertise tasks was assessed by means of an EEG.

In the expertise task, participants were presented with potential taxi routes within the city of Graz and instructed to memorize them. No time-restriction was applied for this memorizing phase. After each route, the names of several streets in Graz were displayed on the computer screen (Fig. 1a). Participants were asked to decide whether or not the street crosses the route in question, and to respond by pressing YES or NO buttons. Altogether, two routes with 30 street names each (in sum 60 items) and one practice route (with only 5 items) were presented. The intelligence task was developed from the subtest 'Wege erinnern' (memorizing paths) of the ''Berliner Intelligenzstruktur-

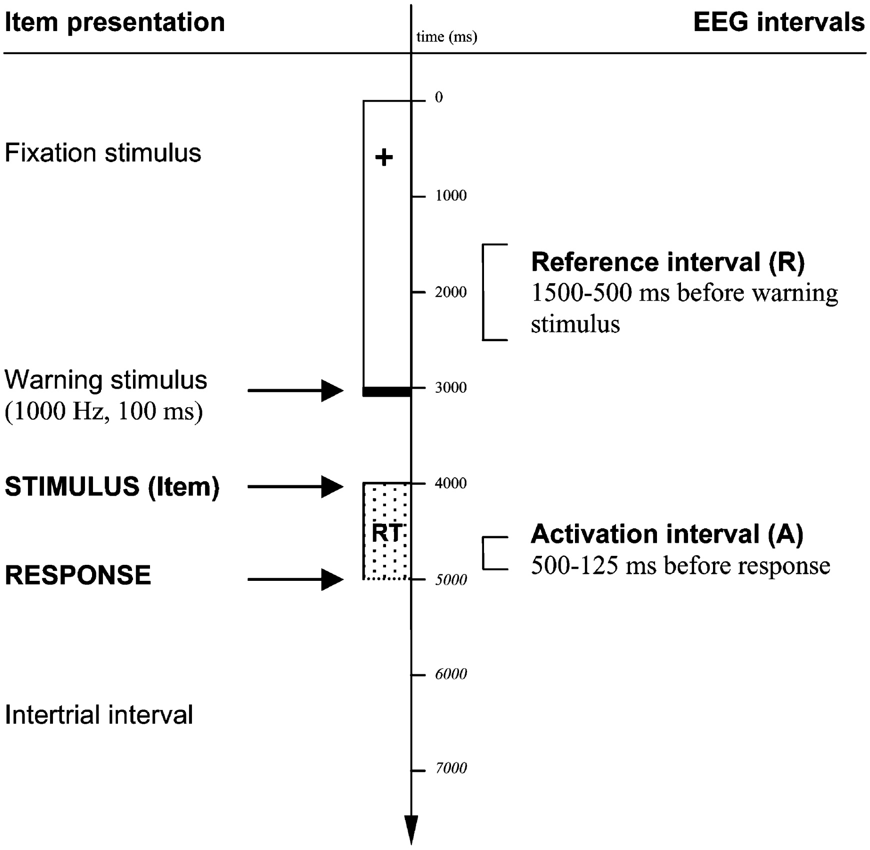

Fig. 2. Timing of the item presentation and the relevant EEG intervals. Please note that the reaction time (RT) was variable.

Test'' (BIS-4; Jäger et al., 1997) and did not relate to participants' prior knowledge. Within a time limit of 30 s, participants had to memorize a route on a fictitious, abstract city map (Fig. 1b). Blank maps displaying a red point instead of the previously shown route were then presented. Participants had to decide whether the previously memorized route ran through the red point or not, and to respond by pressing YES or NO buttons. The intelligence task comprised 12 routes with five blank city maps each (in sum 60 items) and one practice route. In both tasks, instructions stressed speed and accuracy.

Participant's psychometric intelligence was assessed using a time-restricted version of the advanced progressive matrices (APM; Raven, 1958). Measures of their personality structure as well as their temporary mood in the EEG session were included as control variables (cf. Fink et al., 2002) and were assessed by administering the German version (Borkenau and Ostendorf, 1993) of the NEO-FFI by Costa and McCrae (1985) and a self-report inventory on temporary mood (Eigenschaftswörter-Liste; Janke and Debus, 1978).

4.3. Procedure

The session started with the measures of intelligence and mood. The electrodes were then mounted, the participant sat down on a comfortable chair in the EEG recording room, and a 3-min EEG was taken under resting conditions with eyes closed. To present the expertise and intelligence tasks, a PC with an external response console consisting of two horizontally arranged buttons for the YES responses at the top, and two horizontally arranged buttons for the NO responses at the bottom of the console was used. Half of the participants started with the intelligence task, while the other half started with the expertise task. After a short break of 3–5 min, the participants completed the personality questionnaire. A 3-min spontaneous EEG with eyes open was then recorded. Finally, participants worked on the other computerized task (intelligence or expertise, respectively).

The timing of the item presentation is depicted in Fig. 2. At the beginning of each trial, a visual fixation stimulus ('+') was presented on the computer screen for 3000 ms, followed by an auditory warning signal (1000 Hz tone for 100 ms). After 4 s, the test stimulus (i.e. the street name in the expertise task and the blank city map in the intelligence task) was presented. Participants responded to the stimulus by pressing either the YES or the NO buttons, whereupon the stimulus was deleted from the screen. Each response was followed by an intertrial interval of 3150 ms.

The EEG was measured by means of gold electrodes located in an 'electrode cap' in the following 27 positions: F_Z, F_3, F_4, F_7, F_8, FC_1, FC_2, FC_5, FC_6, C_Z, C_3, C_4, T_3, T_4, CP_1, CP_2, CP_5, CP_6, P_Z, P_3, P_4, PO_1, PO_2, T_5, T_6, O_1, O_2 (according to the international 10–20 system); a ground electrode was located between F_Z and C_Z. The EEG was monopolarly recorded at a sampling frequency of 256 Hz with a nose electrode as reference. To register eye movements, an electrooculogram (EOG) was recorded by means of two gold electrodes placed diagonally above and below the right eye. Electrode impedances were kept below 5 kΩ for the EEG and below 10 kΩ for the EOG.

Cortical activation was quantified by analysing the event-related desynchronization (ERD; Pfurtscheller and Aranibar, 1977; see also Pfurtscheller and Lopes da Silva, 1999), based on the fact that the amount of alpha power decreases during cognitive tasks (an 'activation interval') compared with a resting state (a 'reference interval'). The period from 1500 to 500 ms before the warning stimulus (during the presentation of the fixation stimulus) was taken as the reference interval (R) and the period from 500 to 125 ms prior to participants' response as the activation interval (A) (Fig. 2). This interval was selected on the basis of the shortest individual trial reaction times, which were 695 ms for the expertise task and 766 ms for the intelligence task, in order to ensure that the activation interval does not include time periods before the stimulus presentation. All EEG trials were visually inspected with respect to eye or muscle artifacts, and those judged to contain artifacts were excluded from further analyses.[1] The amount of ERD was quantified by calculating the percentage decrease (or increase) in alpha power (μV^2) from the reference interval to the activation interval, according the following formula: $\%ERD=((R-A)/R)\times 100$. Positive %ERD values indicate decreases in alpha power (cortical activation or desynchronization) and negative %ERD values indicate increases in alpha power (cortical deactivation or event-related synchronization (ERS)). These %ERDs were analysed within three alpha bands which were individually determined for each participant using the individual alpha frequency (IAF) as an anchor frequency (cf. Klimesch, 1999): Lower1 alpha band ($L1=(IAF-4\ Hz)$ to $(IAF-2\ Hz)$), Lower2 alpha band ($L2=(IAF-2\ Hz)$ to IAF) and Upper alpha band ($U=IAF$ to $(IAF+2\ Hz)$). Ability- and task-related effects were expected to occur primarily in the Upper alpha band, as this band is assumed to be particularly sensitive to information-processing demands, whereas the two lower alpha bands reflect some kind of unspecific basic alertness and attention processes (cf. Pfurtscheller and Lopes da Silva, 1999). This pattern of results has been found in previous ERD studies examining the relationship between intelligence and neural efficiency by means of different types of cognitive tasks (cf. Neubauer et al., 2002).

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[1] The criteria for inclusion of a subject for further ERD analyses was at least 10 remaining artifact-free trials per task. It is important to note that *all* artifact-free EEG trials (correctly and incorrectly solved items) were included in the analyses. This was done in order to maximize the reliability of the ERD data by aggregating as many artifact-free EEG data as possible. We are aware of the problems possibly associated with analysing correct and incorrect trials, it should be mentioned, however, that the number of incorrect trials was quite low in both tasks (Section 5).

5. Results

For statistical analyses, the total sample was divided into two groups by median split based on their psychometric intelligence (as measured with the APM). The group with lower IQs ($n=15$) included participants with APM scores ranging from 14 to 28 ($M=21.53$, S.D. $=4.82$), the higher IQ group ($n=16$) comprised participants with APM scores ranging from 29 to 39 ($M=33.31$, S.D. $=3.32$). No differences ($P=0.36$ in a MANOVA) between the two groups were found in the control variables ('Big Five' personality traits and temporary mood states during the EEG session).

Achievement ranged from 50 to 60 ($M=55.65$, S.D. $=2.65$) in the expertise task and from 44 to 58 in the intelligence task ($M=49.45$, S.D. $=4.33$). The APM score correlated with achievement in the intelligence task ($r=0.50$, $P<0.01$), but not with achievement in the expertise task ($r=0.10$, $P=0.58$). The median reaction times ranged from 1977 to 4957 ms in the expertise task ($M=2786$, S.D. $=640$) and from 1883 to 6324 ms in the intelligence task ($M=3324$, S.D. $=1059$). Both did not correlate significantly with the score in the APM or the performance in the respective task. As the tasks used in this study can be regarded as 'power' tests rather than 'speed' tests, this result is not surprising and suggests that the score in the two tasks are more valid indicators of performance than are the individual reaction times.

5.1. Event-related desynchronization

The means of the overall %ERDs (averaged over all 27 recording positions for each participant) for the Upper alpha band (on average between 10.21 and 12.21 Hz) and the average topographical distributions for both IQ groups and tasks are depicted in Fig. 3. This figure demonstrates that during working on the intelligence task the lower IQ individuals generally display a larger amount of ERD. Furthermore, the ERD is relatively widespread over the cortex and involves occipital, parietal, temporal and even central areas. The cortical activation of the higher IQ participants is also located in the posterior areas, but the total amount is far lower there, and a slight deactivation (ERS) in the frontal area can also be made out. During working on the expertise task, the IQ groups do not differ markedly in the activated cortical areas or in the amount of activation, except for a slightly higher total ERD in the higher IQ group.

All ERD data were checked for normal distribution before statistical analyses were computed. A two-way ANOVA with IQ group (lower IQ vs. higher IQ) as between-subjects variable and task (expertise vs. intelligence task) as within-subject variable revealed a significant interaction of IQ group and task, $F(1, 29)=6.65$, $P=0.02$, for the %ERD. This interaction suggests that the higher IQ participants displayed a lower total ERD than the lower IQ participants when performing the intelligence task ($P=0.03$ as assessed by the Duncan test), whereas no significant difference in the ERD of the two IQ groups was found in the expertise task ($P=0.23$). As expected, in the Lower1 and Lower2 alpha band, no significant effects emerged.

For a more detailed analysis of the cortical activation, we additionally aggregated the %ERD values for different electrode locations basing on the underlying brain lobe, separately for each hemisphere.[2] A four-way ANOVA with electrode location (frontal, central, temporal, parietal and occipital), hemisphere (left vs. right), IQ group and task was computed and revealed a significant interaction of IQ group and task, $F(1, 29)=6.05$, $P=0.02$ (a result already mentioned above), and a significant main effect of the electrode location, $F(1.56, 45.12)=13.20$, $P<0.01$. As depicted in Fig. 4, the highest ERD could be observed at parietal recording sites, and the lowest activation was found at frontal recording sites. No further (task- and ability-related) effects reached significance.

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[2] The electrode positions were aggregated following Klimesch et al. (1997): Left hemisphere: frontal (F_7, F_3, FC_5), central (FC_1, C_3, CP_1), temporal (T_3, T_5) parietal (CP_5, P_3), and occipital (PO_1, O_1). Right hemisphere: frontal (F_8, F_4, FC_6), central (FC_2, C_4, CP_2), temporal (T_4, T_6), parietal (CP_6, P_4), and occipital (PO_2, O_2). The electrode positions F_Z, C_Z, P_Z were not included in the topographical analyses.

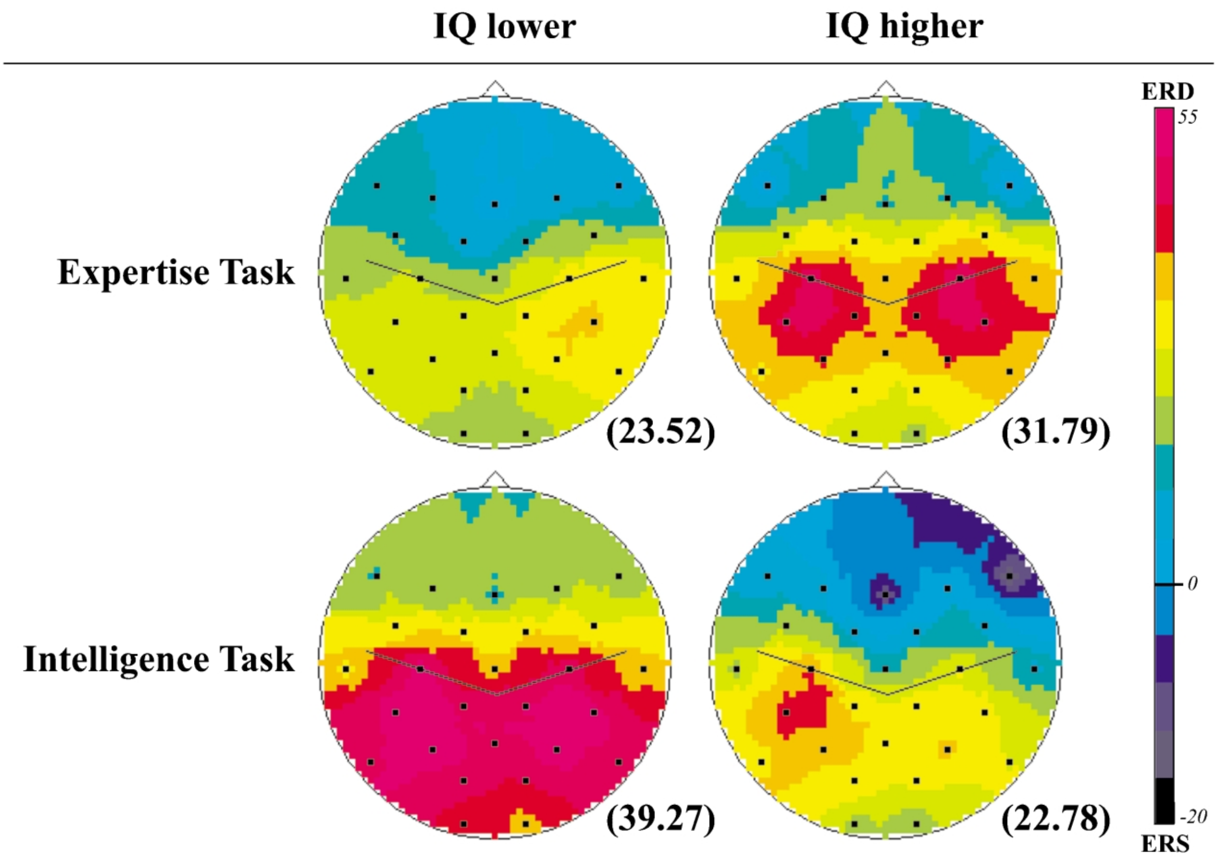

Fig. 3. Average topographical distribution and means of the overall ERD (mean %ERD values are given in brackets) in the Upper alpha band of both intelligence groups and tasks. Warm colours (magenta, red) symbolize a large ERD (indicating a strong cortical activation) whereas cool colours (cyan, blue, dark blue) reflect no or only a weak ERD (or even an ERS; Pfurtscheller, 1992).

6. Discussion

On one hand, the results of this study provide additional support for the neural efficiency hypothesis, according to which more intelligent persons display a lower degree of cortical activation than less intelligent persons during reasoning. In the rather novel, intelligence-related task, the experts' intelligence level impacted both on performance and on the associated cortical activation patterns. This finding is in line with the results of several other studies that have also used the ERD as an indicator for cortical activation. On the other hand, our results suggest that no such neural efficiency patterns emerge when prior knowledge or expertise comes into play. The experts in this study were presented with a task drawing directly on their knowledge of the street network in Graz. In this experimental condition, no intelligence-related differences in the amount of cortical activation were found. This result corresponds to the findings of expertise research and suggests that, once an elaborate domain-specific knowledge base has been constructed, intelligence loses its impact not only on the achievement level, but also in the degree of cortical activation needed to reach this level.

The processing of both tasks seems to involve primarily posterior (particularly parietal) brain

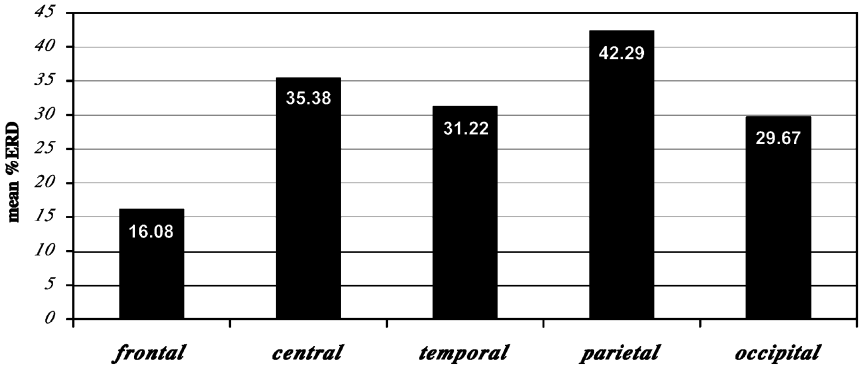

Fig. 4. Topographical distribution of the ERD in the Upper alpha band averaged over both intelligence groups and tasks, separately for five cortical areas. The mean %ERD values are depicted in the bars. Post hoc comparisons by means of the Duncan test revealed significant differences between frontal and the other four areas, between parietal and temporal, and between parietal and occipital areas (all P's <0.01).

regions as topographical analyses of the cortical activation revealed. Also considering the findings of previous studies in the context of information processing and ERD (cf. Pfurtscheller and Lopes da Silva, 1999), this result comes up to the expectations. Furthermore, the topographical distribution of the cortical activation did interact neither with the task nor with the subjects' intelligence level, indicating that the focus of activation is generally located at posterior (parietal) regions. This seems particularly interesting as the expertise task and the intelligence task actually place different demands on the subjects' mnemonic systems. While the former is mainly related to prior knowledge located in long-term memory, the latter demands temporary memorizing of the previously presented abstract routes. Although different cognitive processes and different memory systems might have been involved in the expertise and the intelligence task, the topography of the ERD as well as the frequency band in which ERD occurred (the Upper alpha band) were comparable for both tasks. This finding rules out alternative interpretations tracing the lack of ability-related differences in the expertise task to an insensitivity of the ERD in the Upper alpha band for this special type of task.

As both tasks employed in this study are not completely comparable with regard to their underlying cognitive processes, it could be further supposed that one task (in our case, the expertise task) might have been too easy to evoke intelligence-related cortical activation patterns. This interpretation, however, does not seem to be very plausible either, as the neural efficiency phenomenon could have been confirmed in other studies even when simpler cognitive tasks (so-called elementary cognitive tasks) and tasks that can also be regarded as (semantic) long-term memory tasks were employed (e.g. Neubauer et al., 1999, 2002). Consequently, the results of this study seem to provide a first jigsaw piece in the question for the relationship between (prior) knowledge or expertise and the neural efficiency phenomenon.

Although the experts' degree of neural efficiency in the domain-specific task appears to be largely independent of intelligence, the neural efficiency phenomenon might be involved in a different way here—possibly as a concomitant of expertise development through long-term practice. Haier et al. (1992a) found that several weeks' practice of the complex computer game 'Tetris' led to a decrease in brain activation as assessed by glucose metabolism during playing the game. Practice seems to enhance neural efficiency—and if this is the case for a short-term practice period, it should certainly hold true for the long period of preparation needed to achieve the level of an expert. The current study, however, does not provide an empirical basis for such a conclusion, as only experts of varying IQs and no novices were included in the sample.

Another important question concerns the role of intelligence in the development of expertise. It is thoroughly plausible that general intelligence interacts with the speed with which this level is achieved. At the moment, though it seems too early to draw conclusions about the development of expertise, as the current study was the first attempt to shed light on the expertise–intelligence relationship on the neurophysiological level. Before examining the underlying biological correlates or substrates of the development of expertise, it will be necessary to clarify whether these results can be replicated in other domains of expertise—e.g. more complex domains like chess—and whether the experts' neural efficiency remains independent of their intelligence level, even when more complex demands (e.g. in dual-task paradigms) are involved.

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