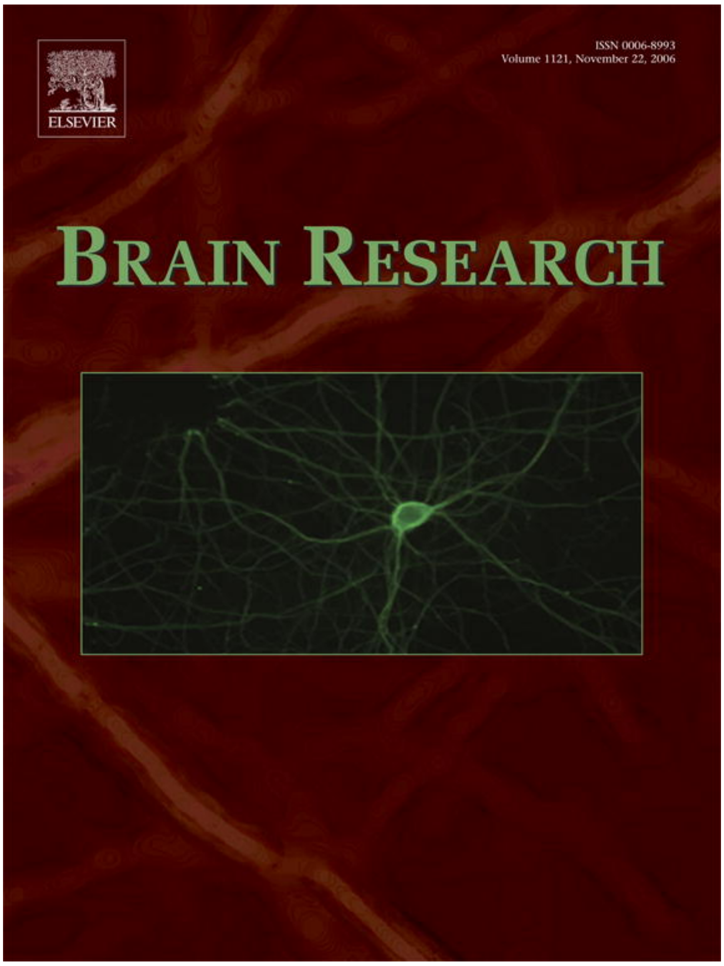
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Research Report

Alpha-band activity reflects reduction of mental effort in a comparison task: A source space analysis

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ABSTRACT

Comparison processes contribute to many core phenomena of social cognition research. Whenever humans judge a given target, they rely on comparisons with a pertinent standard. We propose that comparison processes may be so ubiquitous because they reduce mental effort. To investigate this possibility, we used dense-array Electroencephalogram (EEG) recordings together with a minimum norm source projection approach. As the dependent variable, we examined changes in parietal alpha (8–12 Hz) amplitude during a judgment task. Spectral changes in the alpha frequency range have been reliably related to attentional load, cognitive arousal, or mental effort. Two groups of participants ($n=22$) were procedurally primed to solve a series of target judgments in a more comparative (experimental group) versus more absolute (control group) manner. While the participants performed the critical judgment tasks, we recorded changes in alpha amplitude. Continuous EEG was transformed into a spherical source space using the minimum norm (L2) estimate and spectral changes were subsequently calculated in the source domain. Statistical parametric mapping in combination with permutation statistics was employed to map regions showing significant group differences. Results demonstrate that comparative processing was associated with smaller changes in alpha amplitude than absolute processing. This difference was most pronounced at parietal source locations, where alpha reduction was at a maximum. Temporal analysis suggested that this effect was present particularly during task preparation and execution. We conclude that comparative information processing may reduce mental effort in judgment tasks.

1. Introduction

Human judgment is essentially relative in nature. Abundant empirical evidence demonstrates that targets of all levels of complexity – ranging from simple objects (e.g., Brown, 1953; Helson, 1964) to complex social stimuli (Festinger, 1954) – are evaluated in a relative or comparative manner (Kahneman and Miller, 1986). When humans judge or evaluate a particular target, it seems, they do so by implicitly comparing it to a relevant context, norm or standard (Mussweiler, 2003). This tendency towards comparative information processing is characterized by a striking ubiquity. Social cognition research has provided numerous demonstrations of how strongly comparisons pervade our thinking. Comparisons play a core

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role in areas as diverse as stereotyping (Biernat, 2003), attitudes (Sherif and Hovland, 1961), person perception (Herr, 1986; Higgins and Lurie, 1983), decision making (Kahneman and Miller, 1986; Tversky and Kahneman, 1974), affect (Higgins, 1987), and the self (Festinger, 1954; Higgins et al., 1986).

Why are comparisons so ubiquitous? We suggest that the answer to this question may be tied to one of the most fundamental characteristics of humans as social information processors, namely their need to process information in an efficient manner (Taylor, 1981). People are constantly overwhelmed by the abundance of cognitive tasks they have to master. In light of their limited information processing capacities, they typically have to rely on those processing strategies that save scarce cognitive resources. That is, people often behave as cognitive misers (Taylor, 1981). Consistent with this hallmark principle of social cognition research, ample research attests that people have a strong tendency to rely on efficient modes of information processing such as the use of heuristics (Tversky and Kahneman, 1974) or stereotypes (Bodenhausen, 1990; Bodenhausen and Lichtenstein, 1987; Macrae and Bodenhausen, 2000; Macrae et al., 1994). In much the same way, people as cognitive misers (Taylor, 1981) may rely on comparisons to save scarce cognitive capacities.

In fact, these potential efficiency advantages become apparent upon closer inspection of the psychological mechanisms that underlie comparisons. Recent research demonstrates that comparisons allow the social information processor to focus on a subset of potentially judgment-relevant information (Mussweiler, 2003). Rather than engaging in an exhaustive search of all information that is potentially relevant for the judgment at hand, comparative processing allows judges to selectively retrieve a specific subset of this information (e.g., Mussweiler and Strack, 2000). More specifically, comparisons appear to involve a hypothesis-testing process (Mussweiler, 2003) during which judges primarily focus on hypothesis-consistent information (Snyder and Swann, 1978). Judges who test the hypothesis that the target and the standard of a comparison are similar, for example, selectively search for information which indicates similarity and essentially ignore information which indicates dissimilarity. In this respect, judges selectively focus on a hypothesis-consistent subset of judgment-relevant information. This informational focus in comparative information processing has been demonstrated in a number of recent studies (for an overview, see Mussweiler, 2003). In one of them, for example, participants were induced to compare a target quantity – the average price of a German car – to a numeric standard by testing the hypothesis that target and standard are similar (Mussweiler and Strack, 2000). Subsequent to this comparison, they worked on a lexical decision task which assessed the accessibility of information associated with high versus low car prices. Results indicated that information which is associated with high car prices was more accessible after a comparison with a high rather than a low standard, whereas the reverse was true for information associated with low car prices. This suggests that while carrying out the comparison, participants had selectively focused on information that was consistent with the hypothesis that the target quantity is similar to the numeric standard. Participants who compared the average price of a German car to the high standard, on the one hand, selectively focused on information indicating high prices and basically ignored information indicating low prices. Participants who compared average car prices to the low standard, on the other hand, selectively focused on information indicating low prices and ignored information indicating high prices. When making comparisons, judges thus appear to essentially ignore information that is inconsistent with the hypothesis that guides the comparison process. In this way, processing information in a comparative manner allows judges to significantly simplify the task at hand. Rather than engaging in an exhaustive and representative search of their knowledge base, judges limit themselves to a specific subset of information.

In this respect, comparisons may save scarce cognitive resources. Recent social cognition research has provided initial support for this notion (Mussweiler and Epstude, 2006). Using standard social cognition measures of cognitive efficiency, these studies demonstrate that judges, who were induced to rely more heavily on comparisons during a series of target judgments, were able to make these judgments in a more efficient manner. This research applied a procedural priming logic (Smith, 1994) to manipulate the extent to which judges relied on comparisons during judgment. Participants were asked to report numeric estimates about a series of characteristics (e.g., the number of clubs) of an unknown City X. Participants received a brief description of City X in which some general information (e.g., university town) that was relevant for the critical estimates (e.g., number of clubs) was given. City X was described in terms that made it comparable to participants' hometown. Prior to the critical numeric estimates, participants worked on an ostensibly unrelated task in which they were provided with two pictures. Experimental participants were asked to compare the two pictures in writing (comparative processing), whereas control participants were asked to describe them (absolute processing). Previous research suggests that these different processing modes will carry over to the subsequent target judgment (Mussweiler, 2001; for a survey see, Smith, 1994). As a consequence, participants who were procedurally primed on more comparative processing should rely more heavily on comparisons in judging City X than those who were primed on more absolute processing. In fact, past research indicates that this is the case (Mussweiler and Epstude, 2006). This is, for example, apparent in the fact that after judging City X the pertinent comparison standard (i.e., participants' hometown) is more accessible for participants who were primed on comparative processing rather than absolute processing. In light of the fact that heightened accessibility of a concept typically reflects that this concept was recently used (Higgins, 1996), this suggests that these participants activated information about the standard and compared this information to the City X.

If comparative processing does indeed hold an efficiency advantage, then participants primed on comparative processing should be more efficient in making the numeric estimates. Using two distinct measures of processing efficiency, results suggest that comparative information processing does indeed hold efficiency advantages. For instance, participants were able to give a critical estimate faster, if they relied more heavily on comparisons (Mussweiler and Epstude, 2006). Furthermore, in a dual task paradigm (e.g., Macrae et al., 1994), participants who processed information in a more comparative manner were able to allocate more residual processing capacity to a secondary task, which was apparent in superior performance in that task (Mussweiler and Epstude, 2006). This research provides initial behavioral evidence in support of the notion that comparisons save scarce cognitive resources. Comparative information processing thus appears to reduce mental effort.

The present research was designed to provide more direct evidence for the hypothesized efficiency advantages of comparative information processing by directly examining electrocortical changes that are closely associated with reduced mental effort. Combining methods from social cognition research and the neurosciences can help to develop a broader understanding of the role comparisons play in social information processing. Such a multi-level approach is in line with recent pleas that psychological research and theorizing should build on an integration of diverse methods and procedures (e.g., Cacioppo and Berntson, 1992; Ochsner and Lieberman, 2001). Following such suggestions, we will examine the neural correlates of comparison processes, one of the most fundamental processes in social cognition. Similar attempts have previously been made to examine the neural correlates of social cognitive functions, including stereotyping (e.g., Hart et al., 2000), categorization (e.g., Ito and Cacioppo, 2000; Ito and Urland, 2003) evaluation (e.g., Cacioppo et al., 1996, 1994), self-related knowledge (e.g., Heatherton et al., 2004; Kelley et al., 2002), and interpersonal behavior (e.g., Gardner et al., 2000). The neural correlates of comparative processing, however, remain to be specified.

In the present study, we assessed changes in alpha amplitude in task-related Electroencephalogram (EEG) as a measure of effortful processing. Classic findings in EEG research have suggested that changes in alpha amplitude are a direct and reliable indicator of mental effort in that greater alpha power reduction is typically associated with more effort, arousal, or resource allocation, depending on the experimental task (e.g., Berger, 1938; Ray and Cole, 1985; Fink et al., 2005). Alpha band (i.e., 8 to 12 Hz) spectral changes have thus been used as an inverse measure of cognitive processing since the days of Hans Berger (Berger, 1938). Although recent work has provided evidence for a role of phase-locked alpha oscillations in stimulus processing (Schürmann et al., 1997) and more complex cognitive tasks (Basar et al., 2001), most EEG work points to a parametric reduction of alpha amplitude as a function of task difficulty or attentional demands (Ray and Cole, 1985). Temporal dynamics of alpha reduction have been used to examine memory processes (Klimesch et al., 1999) as well as motor behavior (Pfurtscheller and Aranibar, 1979) and emotional states (Sobotka et al., 1992; Fink, 2005). Taken together, this work has suggested that stimulus- or task-related suppression of spectral power in the alpha range reliably indexes effort associated with well-defined behavioral tasks (see Neuper et al., 2005, for a recent discussion). While the literature on the cortical/sub-cortical origin of alpha modulation is inconclusive, several studies have converged,

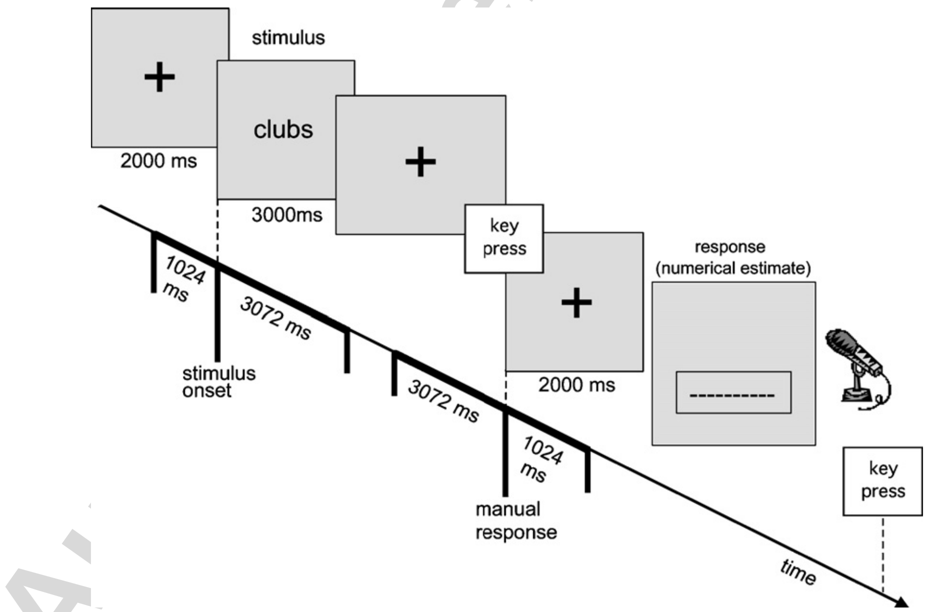

Fig. 1 – Schematic representation of one trial in the judgment task. A fixation cross was present at all times and was shown for at least 2000 ms at the beginning of each trial. Subsequently, a target word was shown, indicating the object whose frequency (number) in the City of X was to be indicated (e.g., a reasonable estimate for the number of clubs in the city X would be "14", and therefore the number 14 would be indicated later on). Participants pressed the SPACE key when they were ready to respond using the numeric pad of a keyboard. After pressing SPACE, they were asked to keep fixating the fixation cross (2000 ms), a period that served as a baseline segment. Mean alpha amplitude changes were determined in four segments, relative to the target presentation and the SPACE response, respectively. For the stimulus-related alpha changes, we used a baseline segment of 1024 ms preceding the target onset; for response-related changes, we used a baseline segment following the response, during a 2000 ms black screen.

suggesting modality and task-dependent foci of alpha suppression (Pfurtscheller et al., 1994). For instance, visual processing appears to be associated with pronounced posterior-parietal alpha reduction, which can be related to changes in the activity at a variety of cortical regions (Hari et al., 1997). In particular, power reduction of alpha oscillations which are not phase-locked to the onset of a visual stimulus (i.e., so-called induced alpha responses, see methods) has been reliably observed at parieto-occipital EEG leads during effortful or attentive processing (Klimesch et al., 2000). Recently, the literature of alpha power modulations has been integrated in a comprehensive review (Klimesch et al., 2006), which concludes that alpha enhancement may be related to inhibitory top-down control of executive functioning. The present task, however, did not tap this kind of process, but rather involved cognitive operations of the kind that are related to widespread activity in attention and memory networks. This task type has been related to alpha decrease both empirically (Ray and Cole, 1985) and conceptually (Klimesch et al., 2006). Thus, if comparative information processing does indeed reduce mental effort, then this should be apparent in differential power changes of induced alpha.

We examined modulation of alpha amplitude as evidence of electrocortical processes that are closely associated with mental effort. More specifically, using the same methods that were previously employed in the behavioral studies (Mussweiler and Epstude, 2006), we induced participants to engage in more or less comparative processing while making a series of target judgments. Employing a procedural priming method (Mussweiler, 2001; Smith, 1994), experimental participants

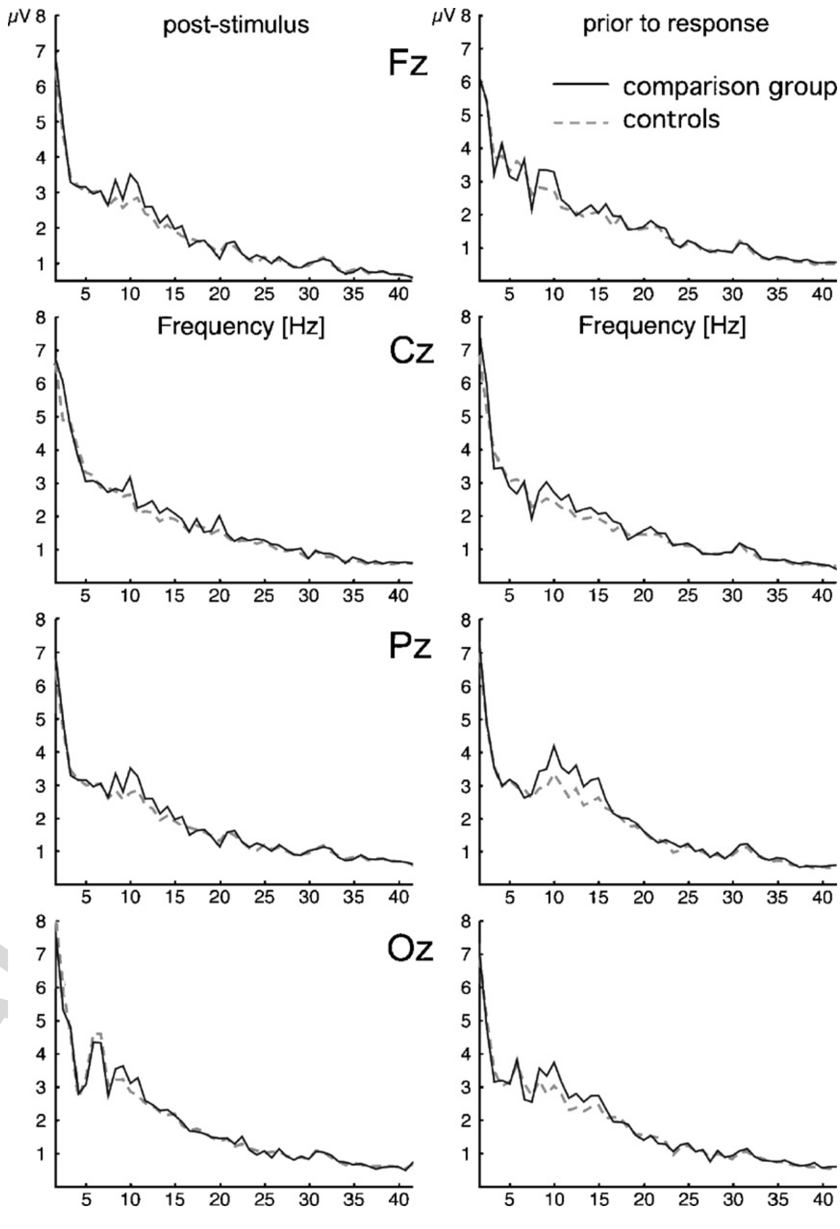

Fig. 2 – Grand mean amplitude spectra for the two time windows under consideration, shown at four midline electrodes for the comparison (solid lines) and the control group (dashed lines). Spectra were obtained for voltage data prior to source space projection.

were induced to rely more heavily on comparative processing when generating a series of numeric estimates about an unknown City X than control participants (see Fig. 1).

We recorded electrocortical changes in alpha amplitude while the estimates about City X were generated. To increase the topographical specificity of the data, we used the minimum norm estimate (MNE). As a reference-independent estimate of voltage currents, this approach also aimed to avoid problems associated with interpretation of spectral parameters derived from scalp voltage data: For instance, bipolar generators are often associated with two distinct topographical maxima in voltage space (e.g., over anterior and posterior regions), but may reflect spectral changes at either of the two brain regions or a third region projecting to the electrodes under consideration (see Hauk et al., 2002, for simulation analyses and an extensive discussion of this issue). The MNE is a mathematical procedure for estimating the primary electric current that underlies the scalp-measured EEG (see Experimental procedures). Applying MNE to the EEG data results in values representing estimated strength at source locations located on a spherical source space, which was used as a model for the brain volume. Continuous MNE data can be submitted to frequency-domain transformation, allowing analysis of alpha changes on the level of modeled sources rather than on the level of voltage maps. We interpreted greater reduction in alpha amplitude as indicating a greater degree of mental effort. Thus, if comparative information processing reduces mental effort, smaller changes in alpha amplitude should result for experimental rather than control participants.

2. Results

2.1. Behavioral data

Participants in the comparison group indicated readiness to give an estimate more rapidly than controls, $t(20)=2.5$, $p<0.05$. Mean response time in the comparison group was 4148 ms (SD=454) as compared to a mean of 5136 ms (SD=1142) in the controls. Given the group differences in variability, we followed this result by a Mann–Whitney-*U*-Test, which yielded the same result, $U=19$, $p<0.01$.

2.2. Regional means analyses

Prior to source space projection, the frequency spectra obtained at midline electrodes were examined for the two groups and two major time windows (post-stimulus, pre-response). The respective amplitude spectra are shown in Fig. 2, suggesting a widespread distribution of alpha modulations, which changed as a function of the between-subjects manipulation. This difference was examined more closely in the minimum norm source space. Topographical distribution of the source estimates for alpha changes across participants showed a pronounced parietal reduction in response to the experimental task (see Fig. 3). This reduction compared to baseline occurred for response-related changes (post-response baseline) and stimulus-related changes (pre-stimulus baseline). We thus selected a group of central parietal source

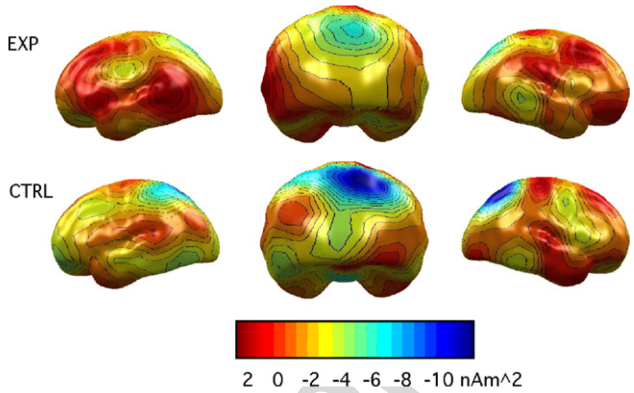

Fig. 3 – Grand mean ($n=11$ per group) distribution of spectral changes in the lower alpha band prior to response onset, compared to a post-response baseline. Greater suppression is shown in shades of blue, projected to a standard brain. Top row: experimental group, bottom row: controls. Changes were calculated using the minimum norm estimate (see Experimental procedures) and thus reflect modulation in terms of source strength.

locations to form regional means for statistical evaluation of overall differences between the groups primed to compare versus not to compare. Absolute alpha source strength did not discriminate between groups during the initial pre-judgment phase, nor differed the absolute amplitude in the baseline segments used for computation of spectral changes during task processing, all $Fs(1,20)<1.5$, n.s.

In terms of stimulus-related changes in alpha amplitude, analysis of variance (ANOVA) for source strength change values showed no differences between groups in any of the alpha bands examined here. A main effect of BAND, $F(2,40)=24.4$, $p<0.01$, reflected stronger decrease for the lower and higher alpha bands, compared to the mid alpha band. No interactions were observed with GROUP.

A different picture emerged for the response-related changes. The experimental group displayed a smaller degree of response-related changes in parietal source strength, compared to the controls, $F(1,20)=7.1$, $p<0.05$. This difference was most pronounced in the low alpha band, GROUP X BAND: $F(2,40)=3.9$, $p<0.05$ (see Fig. 4). The amount of low alpha change was not related to the score in the social comparison orientation scale, resulting in non-significant effects in analysis of covariance and Pearson correlation coefficient between social comparison orientation and low alpha change ($r=-0.09$, n.s.).

2.3. Statistical parametric mapping

In line with ANOVA results reported earlier, unpaired *t*-tests computed for each source location reached the significance level as determined by means of a permutation procedure only in the case of the lower alpha band, for response-related changes. Notably, the very conservative 0.01 criterion was reached at none of the source locations. Fig. 5 displays the source locations reaching the .05 significance level (black) for the low alpha band/response-related changes. The areas marked here indicated greater alpha reduction in the pre-

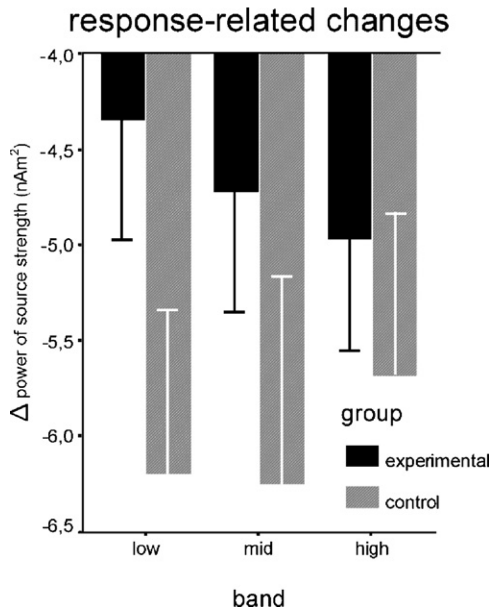

Fig. 4 – Interaction plot showing response-related alpha changes which were sensitive to comparative judgment.

response time range for the control, compared to the experimental group. It deserves mentioning, however, that the post-response baseline underlying these change scores did not differ between groups. As can be seen from Fig. 5, bilateral frontal in addition to left temporal and central parietal cortical sources exhibited differential amplitude modulation. The frontal and parietal areas showing maximum alpha changes in general (see Fig. 3) were thus most strongly associated with significant group differences. This result is consistent with regional mean analyses, corroborating the validity of findings.

3. Discussion

The present findings suggest that comparative information processing holds efficiency advantages. On the electrocortical level, a more comparative mode of information processing was associated with smaller changes of alpha amplitude. In light of the abundant research pointing to a close link between changes in alpha amplitude and mental effort (e.g., Ray and Cole, 1985), our data suggest that comparative information processing reduces mental effort. Compared to control participants who processed the critical judgment tasks in a more absolute manner, the experimental group required less mental effort to solve the very same task. Notably, this held true irrespective of participants' social comparison orientation. Thus, comparative information processing was associated with less mental effort for participants who do versus do not rely on comparisons.

These findings help to understand why comparison processes play such a pivotal role in human judgment and decision making. Research across a variety of domains has demonstrated that human information processing is essentially comparative in nature. Clearly, logical and conversational inferences are important factors that contribute to this ubiquity of comparative processing. Often, human judgments only make sense if a comparison with a pertinent standard is made. The statement "Bob is a hostile person", for example, can only be successfully processed and interpreted, if the pertinent standard is taken into account (Huttenlocher and Higgins, 1971). In addition to such inferences, the efficiency of comparative information processing appears to be a second factor that contributes to the ubiquity of comparisons. People as cognitive misers (Taylor, 1981) tend to rely on efficient processes. The present study suggests that comparative information processing fulfills this efficiency criterion and helps to simplify human judgment. This may be the case, because comparisons reduce the breadth of information that has to be considered before a judgment can be made (Mussweiler, 2003; Mussweiler and Strack, 2000). Rather than trying to obtain a representative set of information about the target, judges who engage in comparative processing only consider the information that is needed to make the critical comparison with the pertinent standard. Focusing on such a subset of information helps people as cognitive misers (Taylor, 1981) to save scarce cognitive resources.

The current study extends previous work in neuroscience and social cognition in a number of ways. It demonstrates that one of the standard electrocortical measures of psychological processes, namely changes in alpha amplitude, can be influenced by subtle procedural priming manipulations (Smith, 1994). To date, changes in alpha amplitude have been observed in a large number of experimental paradigms. For instance, phasic changes in alpha amplitude have been reported as correlates of attentive stimulus processing (Ray and Cole, 1985), affective stimulus processing (Keil et al., 2001), or motor performance (Pfurtscheller et al., 1994), among others. The present research demonstrates that differential patterns of this parameter may also be related to procedural priming (Smith, 1994). Although the two participant groups worked on the same judgment task, they were subtly induced to rely on different processing strategies in doing so. Applying these different strategies was sufficient to yield reliable differences in the amount of alpha reduction. Interestingly, this was only evident for the response-related alpha reduction. While the limited number of trials present in this work

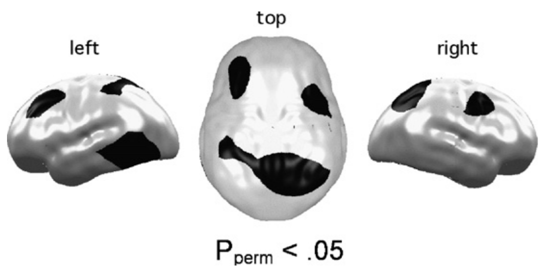

Fig. 5 – Statistical parametric map of permutation *t*-tests between groups, conducted at each source location. Sites shown in black exhibited significantly (Pperm < 0.05) greater alpha reduction for the control, compared to the experimental group in the lower alpha band (centered at 7.81 Hz).

does not allow for a high-resolution time-frequency analysis, the response-related result suggests a locus of differential modulations that occurs late in the judgment process. In particular, aspects of response selection, motor preparation, and task execution may benefit from operating in a comparison mode as induced by procedural priming. Thus, the response-locked analysis may be more sensitive to these late, higher-order processes. Alternatively, cognitive processes related to forming an estimate may temporally extend into the later segment. This notion is supported by the relatively long response times. Furthermore, the fact that the baseline segments used here (pre-stimulus versus post-response) did not statistically differ in terms of alpha amplitude suggests that changes in overall arousal over the duration of a trial cannot account for the specific finding in the response-locked data. Source space projection together with permutation testing of topographical differences showed differential alpha reduction in central parietal cortex, but also in a widespread network encompassing left temporal and bilateral frontal cortex. This pattern of differential activation is consistent with reduced effort in areas mediating visual attention and higher cognitive processes, including verbal encoding of the response. Thus, a plethora of higher cognitive processes may benefit from processing in a comparative manner. It should be kept in mind, however, that changes with respect to the target stimulus did not show such modulation.

In terms of limitations relevant to the interpretation of the present study, one may consider the long durations of Fast Fourier Transform windows (see Experimental procedures) as well as the low number of trials available for analysis. In particular, the estimation of temporal dynamics being achieved by means of complex demodulation or wavelet-transform (e.g., Keil et al., 2001) would be desirable in the context of models of social cognition. While the present experimental paradigm did allow for a high degree of similarity between designs in the social cognition and the EEG laboratories, future work may attempt to enhance the number of trials and modify designs to optimize the measured signal. Another limitation lies in the fact that long segments were used to obtain reliable estimates of amplitude with a low number of experimental trials. Certainly peak frequencies of the bands used here are also sensitive to spectral changes in the high theta or low beta range. Our data do indeed suggest that the selected alpha bands differ in terms of their sensitivity to comparative processing. As discussed in the introduction, such task-dependent modulation of sub-bands within the alpha range has been observed in a variety of other studies (e.g., Klimesch et al., 1998) and has strongly suggested that the functional role of oscillations within the traditional alpha range should be subject to systematic research (e.g., Fink et al., 2005). However, the general pattern of a stronger reduction for the control group was present throughout bands in the present study, although reaching significance for the lower band only. This supports our view that lower frequency activity was suppressed in preparation of the response, which is assumed to reflect 'activation' (e.g., Sobotka et al., 1992) or task-related system changes in brain states (Pfurtscheller and Aranibar, 1979). The topographical distribution of this difference as shown in Fig. 5 suggests that a parieto-frontal network differentially correlated with task performance in the two groups.

To summarize, the present findings highlight one of the most central psychological processes in social cognition. Comparison processes play a crucial role in some of the most central phenomena of social cognition research such as stereotyping (Biernat, 2003), attitudes (Sherif and Hovland, 1961), person perception (Herr, 1986; Higgins and Lurie, 1983), affect (Higgins, 1987), and the self (Festinger, 1954; Higgins et al., 1986). Despite widespread theoretical and empirical agreement, little was known until recently about the psychological mechanisms that underlie comparisons. Recent work has started to shed light on these comparison mechanisms by applying behavioral methods (for a review, see Mussweiler, 2003). The present study extends this work by examining the neural correlates of comparison processes with the help of standard neuroscience methods. In combination, both approaches may help to shed light on one of the most central characteristics of human information processing, namely the tendency to process information in a comparative manner.

4. Experimental procedures

4.1. *Participants*

We recruited twenty-two healthy adult participants (16 females) from the University of Konstanz. Their mean age was 24.5 years (SD = 3.7). Two participants were left-handed. They were retained in the sample as they did not show any signs of differential lateralization or outlying brain response pattern and were assigned to two different experimental groups. All subjects were paid a small financial bonus of 10 Euros (approximately 15 USD). The two experimental groups were matched for age in a pair-wise manner, to avoid possible confounds with age-dependent EEG changes in the alpha range.

4.2. *Materials and procedures*

Upon arrival in the laboratory, participants were greeted by the experimenter and given the Edinburgh Handedness Inventory (Oldfield, 1971) to measure their handedness. Subsequently, an electrode net (see below) was applied and participants were led to the EEG cabin. Here, they were seated on a comfortable chair. They were instructed that they were participating in a study on memory and stimulus processing, which would involve answering questions about a fictional city.

Participants first worked on the procedural priming task, a paper and pencil version similar to that used in previous experiments (Mussweiler and Epstude, 2006). The content of the priming task was unrelated to the critical judgment task: Subjects were confronted with two sketches of works by Albrecht Dürer. For about one half of our participants (experimental group), the two sketches were presented on the same page. These participants were explicitly instructed to compare the two pictures and to write down similarities and differences between them (comparative processing). For the other half of our participants (control group), the two sketches were depicted on two separate pages. These participants were asked to describe each of the individual scenes separately (absolute processing). Participants were randomly assigned to one of these conditions.

After completion of the priming task, participants worked on the critical judgment task, which was presented on a 19″ computer screen. A chin support ensured that the viewing distance of about 70 cm remained constant during the whole experiment. Subjects first received written instructions in which they were asked to carefully read the description of City X and to subsequently make a series of numeric estimates about different characteristics of this city. Then, the description of City X was presented on the computer screen. City X was described in terms that made it generally comparable to participants' hometown of Konstanz. More specifically, City X was described as a university town that is situated in a magnificent landscape and has a high standard of living. Some details about the cultural, economical, and educational infrastructure were provided. The provided information had some implications for the subsequent numeric estimates (e.g., a university town is likely to have more clubs) without directly reporting the critical numbers. Participants were given 30 s to form an impression of City X. Subsequently, they gave a total of 16 numeric estimates about different characteristics of City X in randomized order (e.g., number of students, clubs, McDonald's restaurants, etc.). Each estimate was prompted by the presentation of a representative term on the screen. For instance, the term "churches" indicated that participants were asked to estimate the number of churches in City X. Each trial consisted of the following sequence (see Fig. 1): A fixation cross was shown for 2000 ms. Subsequently the core term representing the critical dimension appeared for 3000 ms. This time period was chosen to avoid rapid luminance changes during the epoch of interest and to remain as close as possible to the behavioral paradigms stimulating the present study (cf., Mussweiler and Epstude, 2006). Participants then reported their answer in three steps. As soon as they felt ready to give their response, they first pressed the space key on the computer keyboard. This key press was introduced as a measure of the time required for making a decision that was not affected by inter-individual differences in typing skills. It was followed by a 2000 ms black screen/fixation cross period, serving as a baseline segment. Participants subsequently reported their actual estimate by means of the number pad and finally confirmed their response by pressing the space bar once again, which started the next experimental trial. As a control for typing errors, subjects were asked to repeat their estimate aloud, using a microphone. No feedback was provided.

Subsequently, participants were led out of the EEG cabin, the electrode cap was removed and the Social Comparison Orientation Scale (Gibbons and Buunk, 1999; German translation: Jonas and Mikula, 2006) was administered. The questionnaire includes 11 items to measure inter-individual differences regarding the tendency to compare events and aspects of their own behavior and experience with others (e.g., "When I want to find out if I perform well, I usually refer to performance of other people"). Upon completion of this questionnaire, subjects were thanked and debriefed about the aims of the study.

4.3. *Data recording and analysis*

4.3.1. *Behavioral data*

Latency of key presses (space key press indicating that the participant is ready to give an estimate) was measured relative to onset of the visual stimulus indicating the relevant dimension. Given the low trial count, we did not perform outlier correction on individual response time distributions but used the median of the log response time for each participant as the dependent measure. An unpaired *t*-test was calculated to evaluate differences between the two experimental groups.

4.3.2. *EEG recordings*

EEG was recorded continuously from 129 electrodes using an Electrical Geodesics Inc. System. Data were digitized at a rate of 250 Hz and were constrained online by bandpass-filtering between .1 and 100 Hz. Impedances were kept below 50 kΩ, as recommended by the manufacturer.

4.3.2.1. Segmenting and artifact control. Given the ongoing nature of the task, we used three different baseline segments for analysis of spectral changes, to examine possible tonic differences in arousal and different amounts of rest activity during the course of the experiment (see below). Further, this procedure allowed temporal analysis of alpha changes, shedding light on dynamic aspects of comparative processing across time. One pre-judgment baseline segment (3072 ms) was obtained from a single artifact-free segment at the beginning of the recording, following procedural priming and 10 s prior to the first judgment item in each participant. This segment was used to estimate group differences in alpha level after the initial priming. Two further variables were determined to reflect spectral changes with respect to two different baseline segments in each trial: First, we extracted epochs containing voltage data collected 1024 ms before and 3072 ms after onset of the visual word stimulus indicating the dimension, for which a judgment was invited (e.g., McDonald's restaurants). Second, epochs containing data collected 3072 ms before and 1024 ms after pressing the response key were extracted. These epochs were artifact-corrected using a procedure developed by Junghöfer et al. (2000). This method uses a combination of trial exclusion and channel approximation based on statistical parameters of the data. Single epochs with excessive eye-movements and blinks, or more than 20 channels containing artifacts were discarded. This resulted in an average rejection rate of 8% of the trials across groups (i.e., 1.3 out of 16 trials), with groups showing no differences regarding this parameter. For all subsequent analyses, data were arithmetically converted to the average reference, and this reference was used throughout.

4.3.2.2. Source space projection of voltage data. Cortical sources were estimated using a linear transformation of the voltage data as suggested e.g., by Hauk (2004). This so-called minimum-norm or L2-norm approach requires no a priori assumptions as to the location of sources and can be applied to continuous data. Here we used the implementation suggested by Hauk et al. (2002). The origin of the scalp-recorded electric gradient is estimated for each time point using 655 model sources, each being equidistantly arranged on three concentric shells, which represent the head volume (see Fig. 6). At each source location, three orthogonal orientations must be considered, two of which are tangential with respect to the surface of the scalp, and one orientation is radial. The procedure is based on the assumption that at a given time point t, the data vector d, which contains the voltage at each electrode sites, can be described as the product of the leadfield matrix L, which specifies the electrode's sensitivity to the sources, the source current vector j and a noise component ε (Grave de Peralta Menendez et al., 1997).

Solutions for this equation can thus be obtained by multiplying the pseudo-inverse of the leadfield matrix L with the data. The minimum norm estimate for the source current vector j is the mathematically unique solution of the equation, which minimizes the squared current density (j^2 = min). Given the high number of electrodes and the presence of noise, spatial regularization is necessary. We used Tikhonov-Phillips regularization, applied during pseudo-inversion of the leadfield matrix L (i.e., $L^{*}L' + \lambda I$ is pseudo-inverted, with I = identity matrix; see Hauk et al., 2002). Regularization parameters ranged from .021 to .097, thus covering a small range. Residual variance was <4% in each individual, suggesting successful fitting of the electrocortical data. This procedure was applied to each data point in each artifact-free epoch in each participant prior to spectral analysis, yielding 3 time series per source location (one radial, two tangential orientations).

4.3.2.3. Spectral analysis. Transformation of minimum-norm single epochs into the frequency domain was achieved by means of Fast Fourier Transform (FFT). Using MATLAB 6.5.1 and in-house software, Welch's periodogram method was applied to segments of 256 sample points (i.e., 1024 ms), which contained three overlapping FFT windows at 128 sample points each. All windows were cosine-square-tapered prior

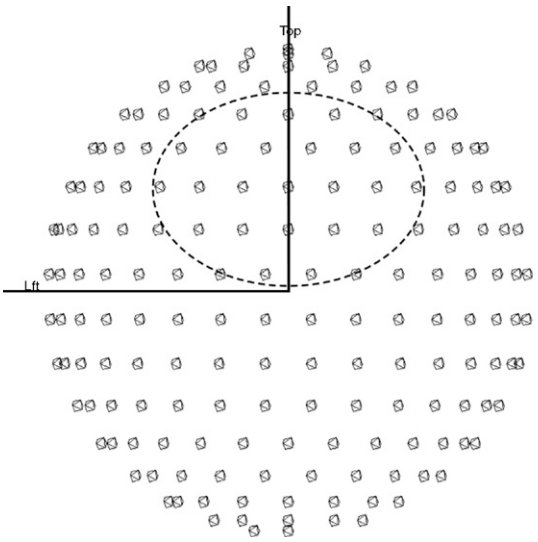

Fig. 6 – Spherical source space used for the present study. Each point on the sphere represents a source location having model dipoles with three orthogonal orientations. The region of interest selected for analyses of variance on regional means is shown in the dashed circle.

to FFT. These steps resulted in a frequency resolution of 1.953 Hz. Therefore, alpha was calculated for frequency bins centered around 7.81 Hz, 9.77 Hz, and 11.72 Hz, respectively. This choice reflected a compromise between two demands: First, good frequency resolution was required, as previous research strongly suggests that different bands within the alpha range may show different sensitivity to task demands (e.g., Fink et al., 2005). Second, the nature of the experimental task and the need for appropriate signal-to-noise ratio required the use of multiple windows within the time segments of interest, i.e., in the temporal vicinity of the stimulus and the vicinity of the button press. Alpha amplitudes were obtained as the square root of the sums of squares for the alpha amplitude of the three orientations at each source location for each time point (Moratti and Keil, 2005). Averaging across epochs enhanced the signal-to-noise ratio of these estimates. Subsequently, changes in the alpha band were computed as amplitude differences with respect to the baseline, resulting in scores of alpha change after presentation of a target word (stimulus-related changes: post-stimulus amplitude–pre-stimulus amplitude) or pre-versus post button-press (response-related changes: pre-response amplitude–post-response amplitude). The post-response segment was used as a baseline for the response-locked analysis, as it was free of spectral changes reflecting motor preparation. Statistical tests showed that alpha power in this window was not different from alpha power in the pre-stimulus window, further corroborating this approach. Time windows for these change values are illustrated in Fig. 1. Resting alpha level after priming, but before performing the experimental tasks was estimated by evaluating the 3072 ms segment recorded after priming (see above). All differences values showed near-normal distributions and we thus did not use additional normalization/transformation. This had the additional advantage of yielding estimates for the size of actual changes on a physical, rather than a statistical dimension.

4.3.2.4. Statistical analysis. Two different statistical approaches were taken to evaluate differences between groups. First, as a parietal focus of alpha changes was expected, we calculated a regional mean across alpha changes at parietal source locations (see Fig. 6), which was evaluated by ANOVA having the between-subject factor GROUP (experimental, control) and the within-subject factor BAND (center frequencies at 7.81 Hz, 9.77 Hz, and 11.72 Hz, i.e., low, mid, and high alpha). Separate analyses were conducted for the initial resting alpha and the two change scores (response-related, stimulus-related). The effects of individual differences as scored on the Social Comparison Orientation Scale (see above) were assessed by an analysis of covariance using the compound score as a covariate. Generally, the same averaged region on the spherical source space was used for ANOVAs, to make sure that these analyses reflect changes along the same dimension and refer to a signal having sufficient signal-to-noise, i.e., parietal alpha amplitude, which was most pronounced across frequency ranges.

Second, to enhance the spatial sensitivity of our procedure, we calculated unpaired t-tests comparing alpha changes of the two experimental groups at each source location across the entire source space, for all frequencies and time ranges.

This method has the advantage of being sensitive to group differences at all locations across the source space and results in topographical maps showing statistical parameters of the expected differences. Because this procedure is associated with an accumulation of alpha error, we used the permutation method suggested by Blair and Karniski (e.g., Blair and Karniski, 1993; Karniski et al., 1994) to assess significance thresholds. In brief, we generated *t*-max distributions for topographies of source locations reflecting a set of *t*-tests by randomly permuting participants 8000 times. For each permutation, the *t*-value having the maximum absolute value in each topography entered the test distribution. Separate permutation distributions were thus determined for different bands, and the most conservative criterion was selected, resulting in critical values of ±2.92 (alpha=.05) and ±3.41 (alpha=.01) for the stimulus-related segmenting and ±2.81 (alpha=.05) and ±3.59 (alpha=.01) for the response-related segmenting. Converging evidence of the two statistical procedures (regional mean analysis and permutation comparison of topographies) was taken as evidence for robust effects. In addition, the distribution of values yielding significant effects was visually inspected to ensure that outliers did not contribute to the results.

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