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Representations of visual proportions in the primate posterior parietal and prefrontal cortices

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Abstract

The primate prefrontal (PFC) and posterior parietal cortices (PPC) have been shown to be cardinal structures in processing abstract absolute magnitudes, such as numerosity or length. The neuronal representation of quantity relations, however, remained largely elusive. Recent functional imaging studies in humans showed that blood flow changes systematically both in the PFC and the PPC as a function of relational distance between proportions. We investigated the response properties of single neurons in the lateral PFC and the inferior parietal lobule (IPL, area 7) in rhesus monkeys performing a lengths-proportion-discrimination task. Neurons in both areas shared many characteristics and showed peaked tuning functions with preferred proportions. However, a significantly higher percentage of neurons coding proportions was found in the PFC compared with the IPL. In agreement with human studies, our study shows that proportions are represented in the fronto-parietal network that has already been implicated for absolute magnitude processing.

Introduction

Monkeys are endowed with non-verbal abstract magnitude competence. They are able to discriminate discrete numerosities that are presented simultaneously (Brannon & Terrace, 1998; Nieder *et al.*, 2002) or sequentially (Nieder *et al.*, 2006). Besides numerical quantities, they can also discriminate continuous quantities, such as the lengths of lines (Tudusciuc & Nieder, 2007). Neural correlates of quantitative competence have been found in the association cortices of the frontal and parietal lobes. Single-cell studies in monkeys have identified neurons selectively tuned to absolute discrete (Nieder *et al.*, 2002, 2006; Nieder & Miller, 2004; Tudusciuc & Nieder, 2007) as well as continuous quantities (Tudusciuc & Nieder, 2007, 2009). Neurons in the parietal cortex and frontal lobes of the cortex form the key circuits for processing of abstract absolute quantities, such as time, space and number (Onoe *et al.*, 2001; Sawamura *et al.*, 2002; Dehaene *et al.*, 2003, 2004; Ninokura *et al.*, 2003; Walsh, 2003; Tanji & Hoshi, 2008; Mita *et al.*, 2009; Tudusciuc & Nieder, 2009).

Dealing with absolute magnitudes, however, is often not sufficient to survive and prosper. Animals are thus able to relate set sizes to each other. In group encounters, for instance, deciding whether to fight or flee depends on the relation of the number of individuals in contesting parties (Gallistel, 1990; Feigenson *et al.*, 2004). The animals base their decision to attack another group not only on comparative more-than/less-than assessments; rather, they derive the ratio of group sizes (Feigenson *et al.*, 2004). In such conflicting situations, animals need to derive the relational quantity, or proportion.

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Recently, we showed that rhesus monkeys are able to relate magnitudes. They had to identify the ratio between two different lines, i.e. spatial proportions, irrespective of the absolute lengths of lines (Vallentin & Nieder, 2008). In this study, the monkeys' performance was on a par with human non-verbal proportion-discrimination performance. Just as for numerosity discriminations, both species showed characteristic properties of magnitude discrimination for proportions, such as the distance effect (Vallentin & Nieder, 2008). Moreover, we found single neurons in the prefrontal cortex (PFC) selectively tuned to ratios while the monkeys performed the spatial proportion-discrimination task (Vallentin & Nieder, 2008). The areas where such proportion-selective neurons were found coincided with PFC regions that also house numerosity-selective neurons. A similar observation was made in humans based on functional imaging. Investigating the neural representation of non-symbolic proportions using functional magnetic resonance imaging (fMRI) adaptation, Jacob & Nieder (2009a) showed that both numerosity and proportion are processed by the same dedicated brain areas in the frontal, but also the posterior parietal cortex (PPC). The intraparietal sulcus, in particular, is also activated when adults process symbolic fractions (Ischebeck *et al.*, 2009; Jacob & Nieder, 2009b).

To investigate the respective contributions of the PFC and PPC in monkeys performing a delayed spatial proportion-discrimination task, we recorded single-cell activity in proportion-discriminating macaques. In both areas, we found neurons selectively representing the spatial ratios. The observed similarities and differences of neuronal discharges in these respective locations may help to elucidate the fronto-parietal network involved in absolute and relative magnitude judgements.

Materials and methods

Stimulus design

Spatial proportions were specified by the ratio of the length of two horizontal lines 0.5° of visual angle above and below the centre of a grey background circle (12° of visual angle in diameter; Fig. 1). Monkeys viewed a sequence of two displays separated by a memory period, and had to evaluate if the ratio that was shown in the sample period (1 : 4, 2 : 4, 3 : 4, 4 : 4) was the same as in the test phase. To prevent the monkeys from using pattern-recognition strategies, we generated new stimuli for every recording session and controlled for possible confounds. In the standard stimuli, the length of the reference line varied between 1.5° (50 pixels, on a 15-inch monitor with a resolution of 1024 × 768 pixels) and 6° of visual angle (200 pixels), and the test line varied accordingly to specify one of the four proportions. The horizontal position of the test line changed randomly. We intermingled the standard protocol with two control protocols. In the first, we kept the reference line constant (2.5° of visual angle), while the test line was adjusted to 0.625° (1 : 4), 1.25° (2 : 4), 1.875° (3 : 4) and 2.5° (4 : 4) of visual angle. In the second, the length of the test line was fixed at 1.5° of visual angle, while the length of the reference line changed between 1.5° and 6° of visual angle. The sample and test stimuli were never identical. We generated the displays randomly every day by shuffling relevant item features (e.g. position and size; see Vallentin & Nieder, 2008).

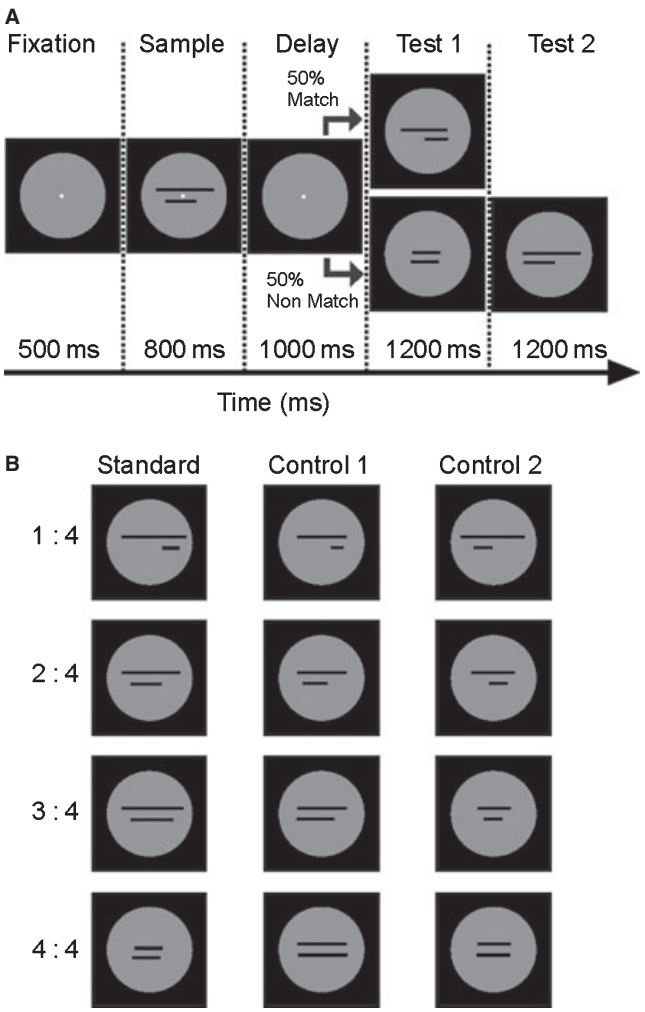


FIG. 1. (A) Behavioral task. To initialise a trial, the monkey had to grab a bar and fixate a fixation spot. The monkey had to memorise a sample stimulus (presented for 800 ms) for 1000 ms until the test appeared. If the first test was a match, the monkey had to release the bar to get a reward. If it was a non-match, the monkey had to wait until the second match and release the bar during the second test presentation to get a reward. (B) Example standard and two example control stimuli sets (see text) with ratios 1 : 4, 2 : 4, 3 : 4 and 4 : 4.

Behavioural protocol

We trained two rhesus monkeys (*Macaca mulatta*) in a delayed match to sample task (DMS-task) to discriminate the four proportions. To start a trial, the animals had to grasp a bar. Then a fixation spot appeared, and they had to start fixating for 500 ms. A sample stimulus was presented for 800 ms, which the monkeys had to memorise during a delay period of 1000 ms. Then the animals were allowed to move their eyes freely and were confronted with the first test. To receive a reward, the monkeys had to release the bar if the first test (1200 ms) showed the same ratio as presented during the sample (match), or to keep holding the bar if a different ratio was shown (non-match). In the latter case a second test was shown, which was always a match (Fig. 1A). We showed standard stimuli with varying lengths of both lines depicting the proportion (Fig. 1B). In addition, we had two types of control stimuli. We either held the absolute line length of the reference line constant and adjusted the test line, or we kept the line length of the test line constant (Fig. 1B). Trials were randomised and balanced across all relevant features (match vs. non-match, standard vs. control). Each monkey performed between 400 and 900 correct trials per recording session. The behavioural and electrophysiological data presented in the current study result from 31 recording sessions in monkey M and 32 recording sessions in monkey H.

Recordings

Electrophysiological recordings were made from the right hemisphere of the lateral PFC centred around the principal sulcus, as well as the inferior parietal lobule (IPL, area 7) near the cortical surface (1–3 mm recording depth) of two behaving monkeys in accordance with the guidelines for animal experimentation approved by the Regierungspraesidium Tuebingen, Germany. During one recording session, arrays of four to eight tungsten microelectrodes (1 MOhm impedance) were simultaneously positioned in the PFC and IPL. The electrodes were lowered in pairs attached to screw microdrives. The exact positioning of the electrode was ensured by fixing the microdrive to a grid with 1-mm spacing. The recording sites were anatomically reconstructed with the use of exact stereotaxic coordinates and magnetic resonance scans from each monkey. The data were acquired from both areas simultaneously. In addition, we monitored the monkeys' performance. Behavioural and neuronal data were measured during the same experiment (Vallentin & Nieder, 2008). Neurons were selected at random; no attempt was made to search for task-related activity. Waveform separation was performed offline applying mainly principal component analysis (Plexon systems). Eye position was monitored with an infrared eye-tracking system (ISCAN, Burllington, MA, USA).

Data analysis

Selectivity

Sample activity was derived from an 800-ms interval after stimulus onset shifted by the individual response latency of each neuron

(Vallentin & Nieder, 2008). For the delay period, activity was summed in a 800-ms interval starting 200 ms after delay onset. Sample and delay activity were analysed in two windows of 400 ms to account for early and late responses (see Vallentin & Nieder, 2008). The selectivity of a neuron was determined by calculating a two-way ANOVA ($P < 0.05$) for each cell, with proportion (1 : 4, 2 : 4, 3 : 4, 4 : 4) and stimulus type (standard, control 1, control 2) as factors. Only cells showing a significant main effect of proportion ($P < 0.05$), but no significant main effect of stimulus type or interaction, were classified as proportion selective, and the proportion eliciting the largest spike rate was defined as the preferred proportion. For neurons that showed a main effect for proportions in both the sample and the delay phase, we calculated an additional modulation index. We averaged the activity in the sample and delay phase for the different proportions, calculated a tuning curve and defined the modulation index (MI):

$$\mathrm{MI} = (M\_\mathrm{max} - M\_\mathrm{min})/(M\_\mathrm{max} - M\_\mathrm{min})$$

where M_max is the maximum modulation (mean firing rate) of the neuron (in response to the preferred proportion) and M_min is the minimum modulation (mean firing rate) of the neuron (in response to the least preferred proportion).

Sharpness and strength of selectivity

We computed two indices to evaluate the sharpness and the strength of the selectivity of the neurons. The selectivity strength index (S_st) was calculated using the formula:

$$S\_\mathrm{st} = (FR\_\mathrm{max} - FR\_\mathrm{min})/(FR\_\mathrm{max} + FR\_\mathrm{min})$$

where FR_max is the maximum firing rate of the neuron (in response to the preferred proportion) and FR_min is the minimum firing rate (after the least preferred proportion). Thus, the selectivity strength index can assume values between 0 and 1. Values close to 1 indicate that the cell is highly selective. The selectivity sharpness index (S_sh) was calculated using the formula:

$$S\_\mathrm{sh} = FR\_\mathrm{max} - FR\_\mathrm{median}$$

where FR_median is the median value of the distribution of average firing rates of the neuron for the four proportions presented. This index takes into account the responses of the neuron to each of the four proportions, as opposed to the strength of selectivity index, which only considers the preferred and the least preferred of the stimuli. The higher the value of S_sh, the sharper the tuning is for the preferred proportion.

Time course of selectivity

The time course of selectivity was assessed by using a sliding window receiver operating characteristic (ROC) analysis (Green & Swets, 1966). We compared two distributions of firing rates, one elicited by the preferred proportion (hit rate) and the other elicited by the least preferred proportion (false positive rate). The area under the ROC curve is a quantitative measurement of how well the two distributions are separated, i.e. how well a neuron discriminates between the preferred and the least preferred proportion [area under the curve (AUC) value of 0.5 means identical distributions, AUC value of 1 means completely separated distribution and, thus, perfect discrimination]. To evaluate the time course of selectivity we computed a sliding ROC analysis in 100-ms windows that were slid in 20-ms steps. We computed the selectivity profile between fixation onset and beginning of the delay period (2300 ms). The sliding AUC was calculated for every proportion-selective neuron. T-tests were used to test for significant differences between the distributions of the mean AUC values (sample vs. delay, PFC vs. IPL) in a 800-ms window in the sample period (starting 100 ms after stimulus onset) and delay period (starting 200 ms after delay onset). Response latency was determined by comparing the original AUC with the AUC obtained by shuffling the data 1000 times, thereby generating random distributions, and finally taking a threshold of 95%. The latency of the selectivity for each neuron is the time after sample stimulus onset, but no later than 350 ms after stimulus onset, when the ROC values of 20 consecutive windows (of 50 ms slid by 1-ms steps) exceeded the 95% upper threshold of the null distribution.

Results

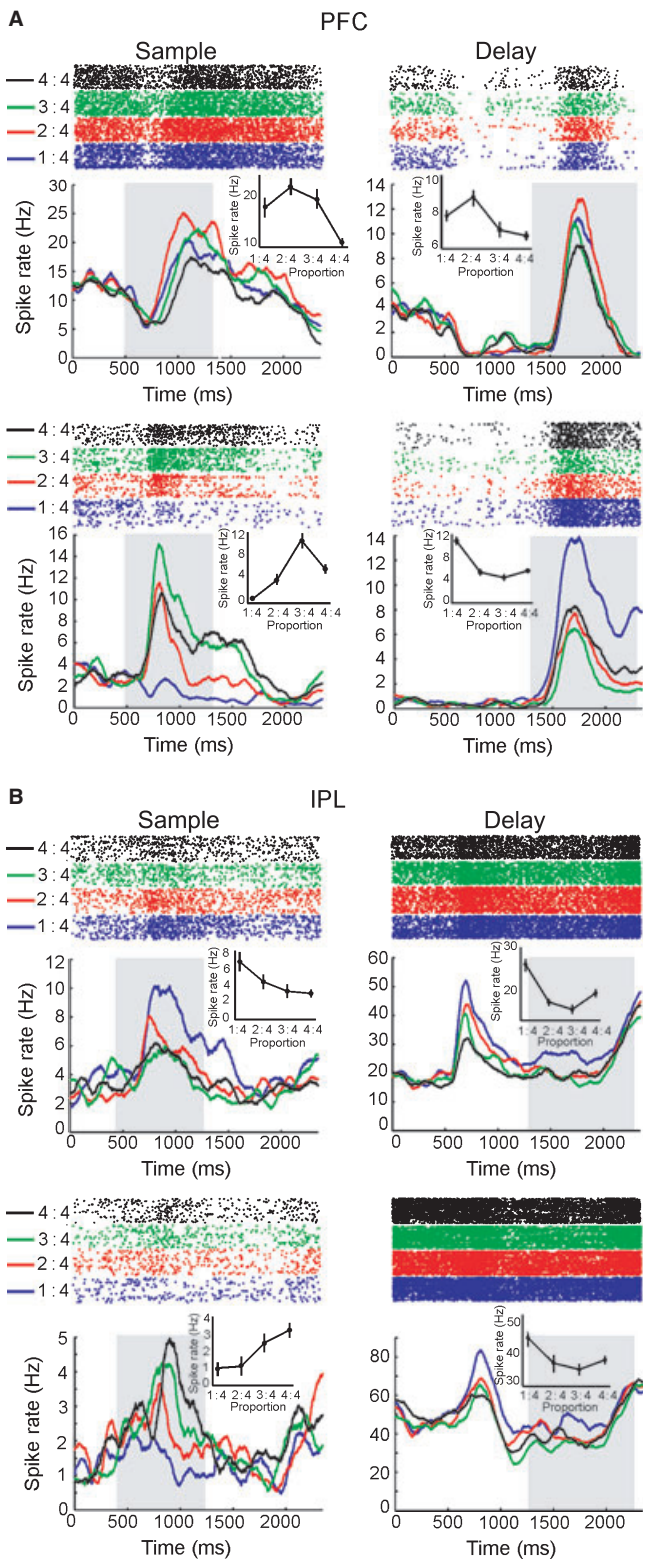
We recorded single-cell activity in response to proportions specified by line lengths in two monkeys discriminating proportions in a DMS-task. The average performance of both monkeys was 85.56% correct and significantly better than chance for all tested proportions and protocols (binomial test, $P < 0.01$). The animals made more mistakes when the proportions were adjacent, and showed improved performance as the distance between the proportions increased (distance effect). Details of behavioural performance are presented in Vallentin & Nieder (2008; Fig. 2A–F).

Firing patterns in PFC and IPL

We recorded 526 randomly selected neurons of the PFC and 308 neurons in the IPL from both monkeys while they performed the DMS-task. We tested the selectivity of the neurons to proportions by using a two-factor ANOVA, which we performed separately for the sample and delay period. To account for the different firing patterns (phasic and/or sustained responses) we performed the analysis in two windows for each time period (see Materials and methods). During sample presentation and the delay phase, many of the tested neurons were significantly tuned to one of the proportions. This tuning was observed irrespective of the absolute lengths of test or reference lines [two-way ANOVA, with factor (sample proportion) × (stimulus protocol), $P < 0.05$].

Figure 2A shows the activity of typical selective PFC neurons tuned to a specific proportion in the sample and delay period. Individual tuning curves (i.e. the mean firing rate for each proportion) during the significant period are presented in the insets. Figure 2B shows representative IPL neurons with a main effect of proportion in the sample or delay phases. In addition to the proportion effect, 79 (15%; sample) and 56 (10%; delay) PFC neurons also showed a main effect of stimulus type and/or interaction effect. In the IPL, 51 (19%; sample) and 44 (14%; delay) neurons showed a main effect of stimulus type and/or interaction effect (Chi square test, $P > 0.05$). Some neurons were selective both during sample presentation and delay phase. Overall, we found 38 PFC and four IPL neurons that showed a main proportion effect in the sample as well as in the delay phase. Typically, proportion preference was similar for both epochs (Pearson's correlation coefficient PFC, $r = 0.54$, $P < 0.001$; Pearson's correlation coefficient IPL, $r = 1$, $P < 0.001$). For these neurons, the MI was not different in both phases (Wilcoxon signed-rank test, two-tailed, $P > 0.05$). When comparing the MIs across the PFC and IPL for all neurons that were either in the sample or in the delay phase tuned to proportion, MIs in the PFC were significantly higher [sample:

MI (PFC) = 0.33, MI (IPL) = 0.24, $P < 0.05$, Mann–Whitney U-test; delay: MI (PFC) = 0.32, MI (IPL) = 0.22, $P < 0.05$, Mann–Whitney U-test). Evaluating the relation between location and selectivity of the neurons did not reveal any clustering of proportion-selective neurons (Fig. 3A).



The tuning functions for both PFC and IPL neurons peaked at the preferred proportion and showed a decrease in activity with increasing distance (Fig. 3B and C). We fitted the neuronal tuning curves with a Gaussian and calculated the tuning width (standard deviation σ). The normalised tuning curves were comparable for the neurons in both recording areas for sample as well as delay activity. Overall, PFC neurons showed a slightly smaller tuning width (mean sample $\sigma = 0.26$, mean delay $\sigma = 0.29$) compared with the standard deviation of the significant PPC neurons (mean sample $\sigma = 0.24$, mean delay $\sigma = 0.32$, Mann–Whitney U-test, $P < 0.05$; Fig. 3B and C, lower panel). These data argue for the labelled-line code for proportions in PFC as well as in PPC because neurons fired maximally to specific proportions.

An error trial analysis (Fig. 3D and E) revealed that, in both areas, the activity decreased for the preferred proportion when the monkey made an error either in the sample or the delay period. PFC neuronal activity decreased to 85 and 88% of that observed during correct trials (100%; Wilcoxon signed-rank test, two-tailed, $P < 0.01$). IPL neuronal activity decreased to 86% in both recording periods (Wilcoxon signed-rank test, two-tailed, $P < 0.01$); this points towards a behaviourally relevant role of proportion-selective cells in the PFC and IPL.

A comparison between PFC and IPL revealed differences in processing line proportions. In total, we found 159/526 (30%) selective cells during the sample presentation in the PFC and 50/308 (16%) in the IPL (Fig. 4A; Chi square test, $P < 0.05$). During the delay period we recorded 183/526 (34%) selective neurons in the PFC and 37/308 (12%) in area 7 (Fig. 4B; Chi square test, $P < 0.05$). Each of the selective neurons preferred one of the four proportions. Most of the selective neurons were tuned to the proportion 1 : 4 (37% in PFC and 36% in IPL). The frequency of proportion-selective neurons was considerably higher in the PFC compared with the PPC (Fig. 4A and B). In the PFC, 30% (sample) and 35% (delay) of the cells were tuned to proportions whereas in the IPL only 16% of the neurons were proportion tuned in the sample phase and 12% in the delay period. The percentage of selective neurons was comparable for the four different proportions, i.e. most of the cells in both areas were tuned to the ratio 1 : 4. Overall, similar percentages of neurons were tuned to the remaining three proportions (Fig. 4A and B).

Strength and sharpness of selectivity for proportions

To evaluate the selectivity strength of the proportion-selective neurons, we calculated the selectivity strength index (S_st). The strength of selectivity is a measure of the power of the tested neuron to discriminate its preferred stimulus from the least preferred one. The mean S_st for PFC neurons was 0.5 for the sample period and 0.47 for the delay period, the mean S_st we obtained from the IPL neurons was 0.48 (sample period) and 0.43 (delay period; Fig. 5A). There was no significant difference between the index values in either area (PFC and IPL) or either period (sample and delay;

FIG. 2. (A) Responses of four prefrontal cortex (PFC) example neurons during the fixation, sample and delay periods. In the top panel, the neuronal responses are plotted as dot-raster histograms (each dot represents an action potential, spike trains are sorted and colour-coded according to the tested proportion). The spike density function depicts the activity in response to a given proportion averaged over all trials and smoothed by a 150-ms Gaussian kernel. The first 500 ms represent the fixation period, which is followed by a 800-ms sample and a 1000-ms delay phase. The different proportions are colour coded. The insets in each panel show the tuning curve (mean firing rates) for the individual neuron during the selective period (left side: sample phase; right side: delay phase). (B) Four example inferior parietal lobule (IPL) neurons. Neurons selective during the delay period were also selective in the sample phase.

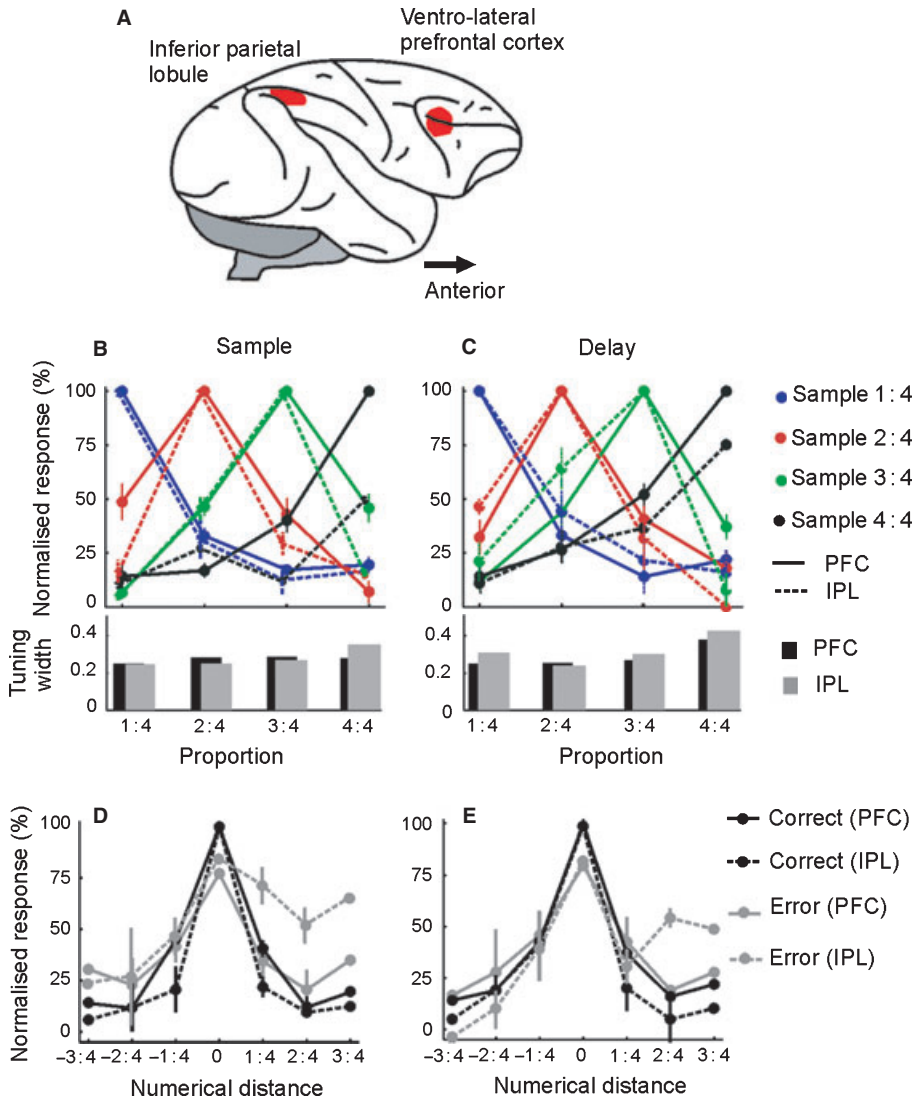


FIG. 3. (A) Lateral view of a rhesus monkey brain. Positions of recording sites in the prefrontal cortex (PFC) and inferior parietal lobule (IPL) of the two monkeys. (B) Normalised responses averaged for PFC neurons (solid line) and IPL neurons (dashed line) preferring the same proportion during the sample (B) and delay (C) phases. Bottom panels show the standard deviation of the tuning curves (half-bandwidth) for PFC (black bars) and IPL (grey bars) across preferred proportions. (D and E) Normalized tuning functions for PFC neurons (solid line) and IPL neurons (dashed line) plotted relative to the preferred proportion for correct trials (black line) and error trials (grey line) during the sample (D) and the delay phase (E).

Mann–Whitney *U*-test, $P > 0.05$). This result indicates that PFC and IPL neurons encode proportion with comparable strengths of responsiveness.

To measure how well a cell discriminates its preferred stimulus from other stimuli, we calculated the sharpness of selectivity index (*S*_sh), which quantifies the width of the tuning curve, i.e. it compares the median firing rate to all proportions with the maximum firing rate to the preferred proportion. Figure 5B shows the average values of *S*_sh for the selective PFC (sample: 2.27; delay: 1.7) and IPL neurons (sample: 1.87; delay: 1.36). In the PFC, the average selectivity sharpness index values were higher for the sample phase than for the delay phase (Mann–Whitney *U*-test, $P < 0.05$), indicating that PFC neurons are more sharply tuned during the sample phase than during the delay phase. For the sharpness selectivity index during the delay period, we observed a significant difference between the PFC and IPL (Mann–Whitney *U*-test, $P < 0.05$). Overall, PFC neurons are more strongly involved in processing the proportion differences.

Time course of proportion discriminability

To assess the temporal dynamics of proportion discriminability, we calculated a sliding window ROC analysis, and computed the area under the ROC curve (AUC) for the proportion-selective neurons (see Materials and methods). Figure 6A shows the average AUC for all PFC, and Fig. 6B the AUC for all IPL neurons separately for sample and delay phases. For PFC neurons, it can be seen that the AUC is increased during the periods the neurons are tuned. There was no such pronounced enhancement for IPL neurons. This indicates that PFC and IPL neurons have a different temporal response characteristic. Between areas, discriminability (AUC values) in the delay phase was significantly higher for PFC neurons compared with IPL neurons (0.54 mean AUC in the PFC vs. 0.52 in the IPL; *t*-test, $P < 0.05$). This difference was not present during the sample period ($P > 0.05$).

Finally, we compared for the two areas the latency of the selectivity onset as determined by the ROC analysis (Fig. 6C). Using a shuffling predictor, we defined selectivity latency by the first significant AUC

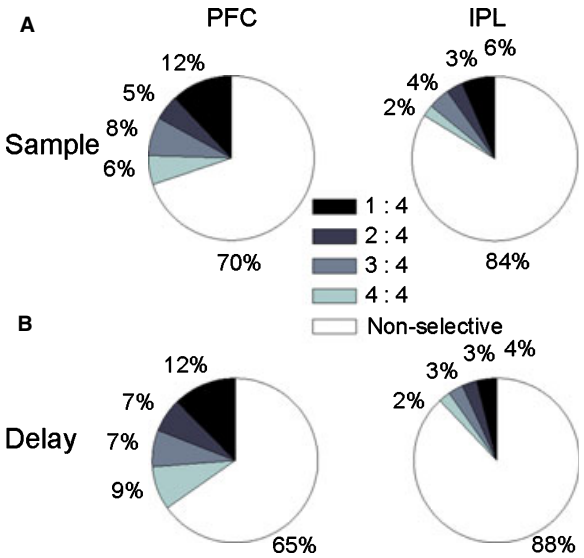


FIG. 4. (A) Frequency distribution of selective neurons in the prefrontal cortex (PFC) and inferior parietal lobule (IPL) in the sample and (B) delay phase.

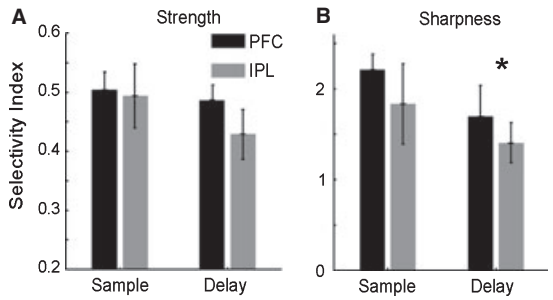


FIG. 5. (A) Selectivity strength index for the proportion-tuned prefrontal cortex (PFC) neurons (black) and inferior parietal lobule (IPL) neurons (grey). (B) Selectivity sharpness index for PFC and IPL neurons. * indicates the significant difference.

value in 20 consecutive selective time windows (50 ms duration), shifted by 1 ms (see Materials and methods). IPL neurons tended to reach the selectivity criterion faster than the PFC neurons (the latency of 33 IPL neurons and 103 PFC neurons could be determined). The median latency was 214 ms and 168 ms for the PFC and IPL neurons, respectively (Mann–Whitney *U*-test, $P > 0.05$).

Discussion

Recording single-unit activity in PFC and IPL simultaneously provided the possibility to compare the respective contributions of these areas during a delayed match to proportion task. We found that neurons in the lateral PFC shared many properties with neurons in the IPL (area 7), confirming that not only absolute numerical (Nieder & Miller, 2004) and spatial quantity (Tudusciuc & Nieder, 2009), but also quantity relations are processed in the fronto-parietal network. However, subtle differences in both areas suggest a specialised role for both areas in processing proportions.

Proportion-selective neurons in both areas showed the same coding scheme. Selective neurons elicit peaked tuning functions to the preferred proportion, i.e. they showed a gradual decrease in firing rate with increasing distance from the preferred proportion. This coding scheme is known as labelled-line code, already described for neurons tuned for specific magnitudes and quantities (Nieder & Miller, 2003; Nieder & Merten, 2007; Merten & Nieder, 2009; Tudusciuc & Nieder, 2009). An investigation of the tuning characteristics revealed both similarities and differences between the processing of non-symbolic proportions in the monkey PPC and PFC. The tuning width (as measured by the width sigma of the gauss-fits) and the strength of selectivity (*S*_st) were equal in both cortical areas, both in the sample and the delay phases. Particularly during the delay phase, however, PFC neurons were characterised by sharper tuning (as measured by *S*_sh) as well as increased discriminability (determined by the area under the ROC curve). This suggests that the PFC has a more prominent role in representing proportions during the memory period. A similar observation has been made for numerosity representations in the macaque brain (Nieder & Miller, 2004).

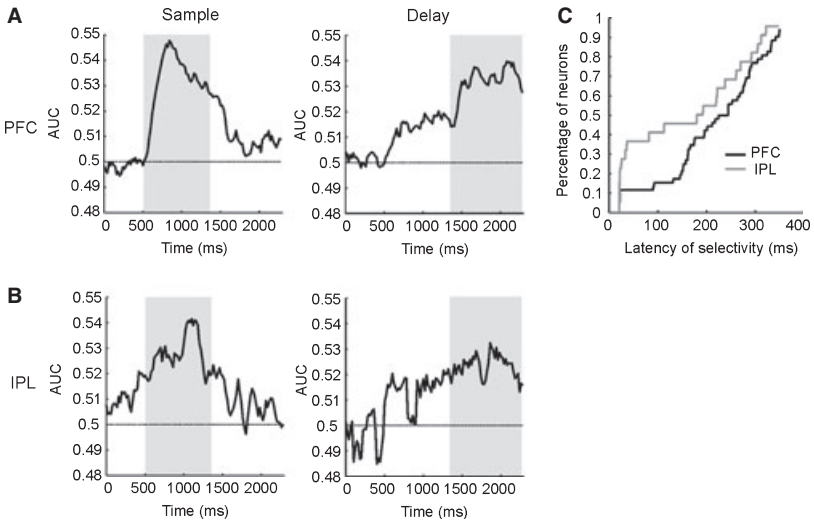


FIG. 6. (A and B) Average area under the curve (AUC) calculated with a sliding window ROC analysis (100 ms windows shifted in 20-ms steps). Neuronal data were divided into sample- and delay-selective cells for both the prefrontal cortex (PFC) and inferior parietal lobule (IPL). (C) Cumulative distribution of response latencies for PFC and IPL neurons during the sample phase. Latencies were determined by comparing the ROC values obtained from the sliding ROC analysis executed with shuffled data with the original ROC values (see Materials and methods).

The most obvious differences between IPL and PFC neurons, however, were related to the overall percentage of selective neurons in a given area and the degree of abstractness in coding relations. Of a random and unbiased pool of recorded neurons, the PFC exhibited a higher proportion of ratio-selective neurons (32% on average for sample and delay phases), whereas only 14% of IPL neurons were tuned to line ratios. In addition, PFC neurons were less responsive to non-numerical stimulus properties, as witnessed by fewer neurons that showed a significant main effect of the stimulus protocol (standard vs. controls) or interactions between main effects (proportions and stimulus protocol).

The IPL constitutes a classic association cortex and is thought to be involved in a diverse set of neural operations, including spatial attention, multimodal sensory integration and oculomotor control (Hyvarinen *et al.*, 1980). Electrophysiological studies have demonstrated that neurons in IPL have response properties ranging from attention-enhanced visual and oculomotor responses (Lynch *et al.*, 1977; Goldberg *et al.*, 1990; Colby *et al.*, 1996) to complex patterns of activity during object visualisation and manipulation (Ohtsuka *et al.*, 1995; Murata *et al.*, 1996). Some neurons in the IPL are also selective for numerosity (Nieder & Miller, 2004). Here we report that IPL neurons are also responsive to visual proportions. According to the classic model of association cortex, sensory information reaches the PPC, and this information is transformed and relayed to the frontal cortex (Schwartz & Goldman-Rakic, 1984; Quintana *et al.*, 1988, 1989; Yajeya *et al.*, 1988; Quintana & Fuster, 1999; Chafee & Goldman-Rakic, 2000). This is in agreement with our qualitative finding that IPL neurons responded earlier to proportions than PFC neurons. A similar result was previously reported for numerosity and line length coding. Nieder & Miller (2004) found that PPC neurons responded faster to sets of dots than did PFC neurons, and Tudusciuc & Nieder (2009) obtained equivalent results for length discriminability. Both for absolute (numerosity) and derived quantities (proportion), the PPC seems to constitute the first processing stage in the cortical hierarchy. We speculate that this information is passed on to the frontal lobe (slightly later) in a subsequent step to gain control over behaviour.

An interesting question is if and how behavioural training would have an impact on single-cell representations of proportions. Neurons both in the PFC (Freedman *et al.*, 2001) and in area lateral intraparietal area (LIP) (Freedman & Assad, 2006) have been shown to adjust category selectivity as a function of training. Our approach does not allow to disentangle putative learning effects. But even if the proportion-coding network might have been amplified according to task demands, a *de novo* creation of proportion-selective neurons seems not parsimonious. First, even without laboratory training, human infants (McCrink & Wynn, 2007) and animals in the wild (Harper, 1982) are spontaneously able to discriminate proportions; this can only be achieved by appropriate neurons. Second, individual tuning of neurons to magnitude categories is just as present in cases where the animal has to accomplish two different quantity-discrimination tasks at the same time (Tudusciuc & Nieder, 2007, 2009). Moreover, it would probably be unjustified to think of representations in the parietal cortex, a classical association area, in behaving animals as purely bottom-up. An elegant study by Freedman & Assad (2009) demonstrated that individual neurons in area LIP integrate visuospatial signals and more abstract task-dependent information during complex visually based behaviours. In this cognitively demanding task, many neurons showed reliable encoding of categorical information of stimuli located way beyond the classical receptive field of the neurons (Freedman & Assad, 2009). Most likely, such general modifications of neuronal properties reflect top-down influences that of course also have to be taken into consideration in our task protocol.

Our findings complement and refine recent functional imaging studies describing selectivity to quantity relations in a parieto-frontal network. Using an fMRI adaptation protocol to investigate automatic quantity processing, a recovery from repetition suppression was detected both for line and numerosity proportions in lateral PFC and PPC (Jacob & Nieder, 2009a,b). Because recovery from blood oxygenation level-dependent adaptation was a function of ratio distance, populations of neurons in the human cortex also seem to be tuned to preferred proportions. Moreover, both numerosity and proportion seem to be processed by the same dedicated brain areas, as witnessed by a strong overlap of the distance effect for numerosity and proportions stimuli. Using the same methodology but presenting fractions in symbolic notation, Jacob & Nieder (2009b) could show that populations of neurons in the human parietal cortex were tuned to preferred fractions and even generalise across the format of presentation. The distance effect was invariant to changes in notation from number to word fractions, and strongest in the anterior intraparietal sulcus, a key region for the processing of whole numbers. The intraparietal cortex was also active in adults solving a fraction comparison problem (Ischebeck *et al.*, 2009). These findings demonstrate that the primate brain uses the same analogue magnitude code to represent both absolute and relative quantity. Together with previous studies in the numerical domain, the current findings indicate a similarity between non-symbolic quantity processing in the human and monkey brain.

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Abbreviations

AUC, area under the curve; DMS, delayed match to sample; fMRI, functional magnetic resonance imaging; IPL, inferior parietal lobule; LIP, lateral intraparietal area; PFC, prefrontal cortex; PPC, posterior parietal cortex; ROC, receiver operating characteristic.

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