Two distinct modes of hemodynamic responses across the human cortex

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ABSTRACT

Functional magnetic resonance imaging (fMRI) detects changes in brain activity by measuring fluctuations in blood oxygenation. This interpretation relies on the mechanism of neurovascular coupling, which closely links changes in neuronal activity to changes in cerebral blood flow (CBF). Whether uniform neurovascular coupling applies to the entire human cortex is yet to be proven. We used blood-oxygenation-level-dependent (BOLD) fMRI along with quantitative fMRI to assess the cerebral metabolic rate of oxygen (CMRO2) associated with both positive and negative BOLD signal changes (ΔBOLD). In contradiction to the canonical hemodynamic model of BOLD signal responses, we found discordant CMRO2 in 12-36% of voxels with significant positive and in 52-66% of voxels with significant negative ΔBOLD. This implies that a considerable number of voxels with negative ΔBOLD exhibit increased metabolic activity and vice versa. During the baseline state, we found a lower oxygen extraction fraction (OEF) and oxygen metabolism in discordant compared to concordant voxels. During task states, ΔOEF replaces ΔCBF as the primary mechanism of oxygen supply in discordant voxels. Thus, we propose OEF as a complementary hemodynamic response type to CBF in regulating oxygen demand in the human brain. In such conditions, the traditional interpretation of positive and negative BOLD signal changes in terms of increased or decreased neural activity will be misleading, and we recommend quantitative fMRI or additional CBF measurements for a more valid interpretation of regional BOLD signal changes in relation to neuronal activity.

INTRODUCTION

Neuronal activity is the brain's primary energy consumer, quantified as the cerebral metabolic rate of oxygen (CMRO2) (Engl & Attwell, 2015). Functional magnetic resonance imaging (fMRI) is a powerful and non-invasive method to localize brain activity during perception and cognition in the cortex of humans and other species (S.-G. Kim & Ogawa, 2012). However, the fMRI signal does not directly measure oxygen metabolism. Instead, it detects changes in cerebral blood oxygenation, which is why it is called the blood-oxygenation-level-dependent (BOLD) signal. Changes in the BOLD signal (ΔBOLD) are interpreted as local changes in neuronal activity. This interpretation is based on the well-known mechanism of neurovascular coupling, which links changes in neuronal activity to changes in cerebral blood flow (CBF) (Attwell et al., 2010; Drew, 2022; Hall et al., 2016; Hillman, 2014; Howarth et al., 2021; Leithner & Royl, 2014; Phillips et al., 2016).

Early studies of the human visual cortex using positron emission tomography (PET) have shown that a modest increase in CMRO2 is accompanied by a much larger increase in CBF (Fox et al., 1988; Fox & Raichle, 1986). A positive ratio of ΔCBF/ΔCMRO2 (*n*-ratio) of approximately 2-4, as observed in these studies, ultimately leads to a positive BOLD response (Ances et al., 2008; Buxton, 2010; Uludağ et al., 2004). Although the regulatory mechanisms of this hemodynamic response are still debated (A. D. Ekstrom, 2021; Hillman, 2014), it is commonly assumed that increased neuronal activity is accompanied by a surplus increase in CBF, likely to maintain a high partial pressure of oxygen in capillaries for diffusion into brain tissue (Buxton, 2020, 2023; DiNuzzo et al., 2023).

At the mesoscopic level, research groups have validated the connection between increased neural spiking or synaptic activity and increased CBF or BOLD signals (Boorman et al., 2010; Devor et al., 2003; Gagnon et al., 2015; Logothetis et al., 2001; Siero et al., 2013). Further studies have demonstrated a direct relationship between incoming spiking activity and positive ΔBOLD when controlling for the extent of sensory input (Heeger et al., 2000; D. S. F. Hyder et al., 2010; Rees et al., 2000; Vanzetta & Grinvald, 1999). Similarly, researchers have reported that decreased neuronal activity or inhibitory processes are associated with negative ΔBOLD (Devor et al., 2007; Fracasso et al., 2022, S. 20; Mullinger et al., 2014; Pasley et al., 2007; Shmuel et al., 2002, 2006; Stefanovic et al., 2004; Wilson et al., 2019). Combined, these studies support the interpretation of BOLD signal changes as localized changes in neuronal activity. However, there is an ongoing debate on how well these findings, obtained primarily from sensory cortices, generalize to the rest of the cortex, particularly in humans.

Several studies have questioned that BOLD signals are consistently related to neuronal activity. For instance, experiments involving pharmacological and oxygenation challenges have shown that CBF or CBV can change without a corresponding change in BOLD signals. This suggests a decoupling of the hemodynamic response from neuronal activity under certain conditions (Nagaoka et al., 2006; Rossetti et al., 2021; Zaldivar et al., 2014; Q. Zhang et al., 2019). This is supported by studies showing no change or even increased metabolism despite significant negative ΔBOLD or ΔCBF (Devor et al., 2008; Martínez-Maestro et al., 2019; Stiernman et al.,

2021). In human imaging, matters are further complicated because the BOLD signal from macroscopic fMRI voxels is a complex amalgamation of microscopic alterations in CBF, cerebral blood volume (CBV), and the oxygen extraction fraction (OEF) during capillary passage (Buxton, 2010; Buxton & Frank, 1997; D. S. F. Hyder, 2010). Moreover, a varying vasculature across brain regions might induce different BOLD signal amplitudes (Shaw et al., 2021). Additionally, various neurochemical processes, beyond direct neuronal activity, are known to modulate the BOLD signal (Boynton, 2011; Cardoso et al., 2012; Das & Sirotin, 2011; A. Ekstrom, 2010; Sirotin & Das, 2009; Tsvetanov et al., 2020).

These studies collectively indicate that different hemodynamic mechanisms can lead to similar macroscopic BOLD signal changes. As a result, the amplitude and sign of the BOLD signal response may not always faithfully reflect changes in neuronal activity. It is important to note that despite substantial evidence for a canonical and linear hemodynamic response in sensory and motor cortices, this may not apply to other brain areas. Accordingly, several studies have shown regional differences in hemodynamic responses, especially between cortical and subcortical regions (Bergel et al., 2020; Devonshire et al., 2012; Roy et al., 2021; Sanganahalli et al., 2016; Schridde et al., 2008; Shaw et al., 2021; Shih et al., 2011). Moreover, it is well known that hemodynamics and vasculature are impaired in certain brain disorders, possibly impacting the comparison of BOLD signal patterns between patients and healthy controls (Buxton, 2010; Fleisher et al., 2009). These observations cast doubt on whether a canonical hemodynamic response can be assumed for each voxel of the entire cortex.

In this study, we investigated the validity of the canonical hemodynamic response by imaging cerebral perfusion and oxygen metabolism in addition to BOLD signal changes across the human cortex. The gold standard for CBF and CMRO2 measurements is ^{15}O PET. Still, it requires an on-site cyclotron, a sophisticated imaging setup, and significant experience in performing multiple experiments within the same individual using three different radiotracers (e.g., CBF: 15O-water, CBV: 15O-CO, OEF: 15O-gas) of short half-lives (Fox & Raichle, 1986; F. Hyder et al., 2016; Ito et al., 2021). Moreover, it is an invasive and demanding approach for participants due to the radioactive exposure and arterial sampling. Over the last two decades, several MRI-based approaches have been established to quantify oxygen metabolism using either gas calibration, R2'-based calibration, or quantitative susceptibility mapping (Alzaidi et al., 2024; Jiang & Lu, 2022). Quantitative BOLD imaging is the most widely used approach to obtain voxel-level hemodynamics and CMRO2 (Bright et al., 2019; Chen et al., 2022; Christen et al., 2012; Göttler et al., 2019; He & Yablonskiy, 2007; Hirsch et al., 2014; Kaczmarz, Hyder, et al., 2020; Kufer et al., 2022; Liu et al., 2020; Pike, 2012; Stone & Blockley, 2017; Yablonskiy et al., 2013; Yablonskiy & Haacke, 1994).

Previously, we have successfully used mqBOLD imaging to study hemodynamic changes in patient groups with vascular pathologies (Gersing et al., 2015; Göttler et al., 2019; Kaczmarz et al., 2021; Kufer et al., 2022) and brain tumors (Preibisch et al., 2017; Tóth et al., 2013; Wiestler et al., 2016). Here, we applied the technique to healthy subjects to investigate assumptions about the hemodynamic response underlying ΔBOLD. Given the heterogeneous vascular composition of macroscale voxels, the diversity of mechanisms influencing the

hemodynamic response, and the partly contradicting findings of a canonical hemodynamic response across brain regions, we hypothesized that ΔBOLD does not reliably reflect canonical changes in oxygen metabolism across the cortex.

RESULTS

We obtained brain imaging data using BOLD and quantitative fMRI while participants carried out four distinct experimental conditions within the same imaging session (Figure 1A & 1B). These four conditions enabled us to identify (1) 'task-positive' regions exhibiting an increase in the BOLD signal, as well as (2) 'task-negative' regions with a negative BOLD response when participants performed a calculation task (CALC). Furthermore, we aimed for (3) positive BOLD responses in the same regions of the 'task-negative' contrast by employing an autobiographical memory task (MEM). We calculated contrast images for the two tasks (CALC, MEM) compared to either a low-level control task (CTRL) or an uncontrolled resting state (REST).

Quantitative fMRI measures CMRO2 as a metabolic proxy of neuronal activity. CMRO2 is calculated according to Fick's principle, incorporating multiple parameter maps for several aspects of the hemodynamic response into a measure of oxygen metabolism (Figure 1C and Methods). Figure 1C illustrates brain slices of non-thresholded parameter maps, averaged across all participants, alongside boxplots with each subject's average gray matter (GM) values in each condition. Table 1 provides the mean values of the individual parameters and CMRO2 across all subjects and conditions.

Table 1

Whole-brain (GM) parameter values, mean ± SD across subjects and conditions.

R2' [1/s]	CBV [%]	OEF [ratio]	CBF [ml/100g/min]	CMRO2 [µmol/100g/min]
5.3 ± 0.4	4.8 ± 0.2	0.39 ± 0.04	44.5 ± 7.2	127.8 ± 18.4

The BOLD signal is a composite signal representing the combined neurovascular and metabolic response lacking the ability to distinguish individual factors. The underlying canonical hemodynamic response model (Figure 1D) assumes several stable relationships that might not be identical for each voxel. The most prominent assumption in response to neuronal activity is that CBF provides excess oxygen to a stimulated region, surpassing the increased metabolic demands. This is described by the *n*-ratio, which commonly adopts values of 2-4, ultimately resulting in a positive BOLD response relative to an experimental baseline (ΔBOLD [%]). In this study, we combined BOLD and quantitative fMRI to test the assumptions of the canonical hemodynamic response model regarding metabolic changes across regions and conditions.

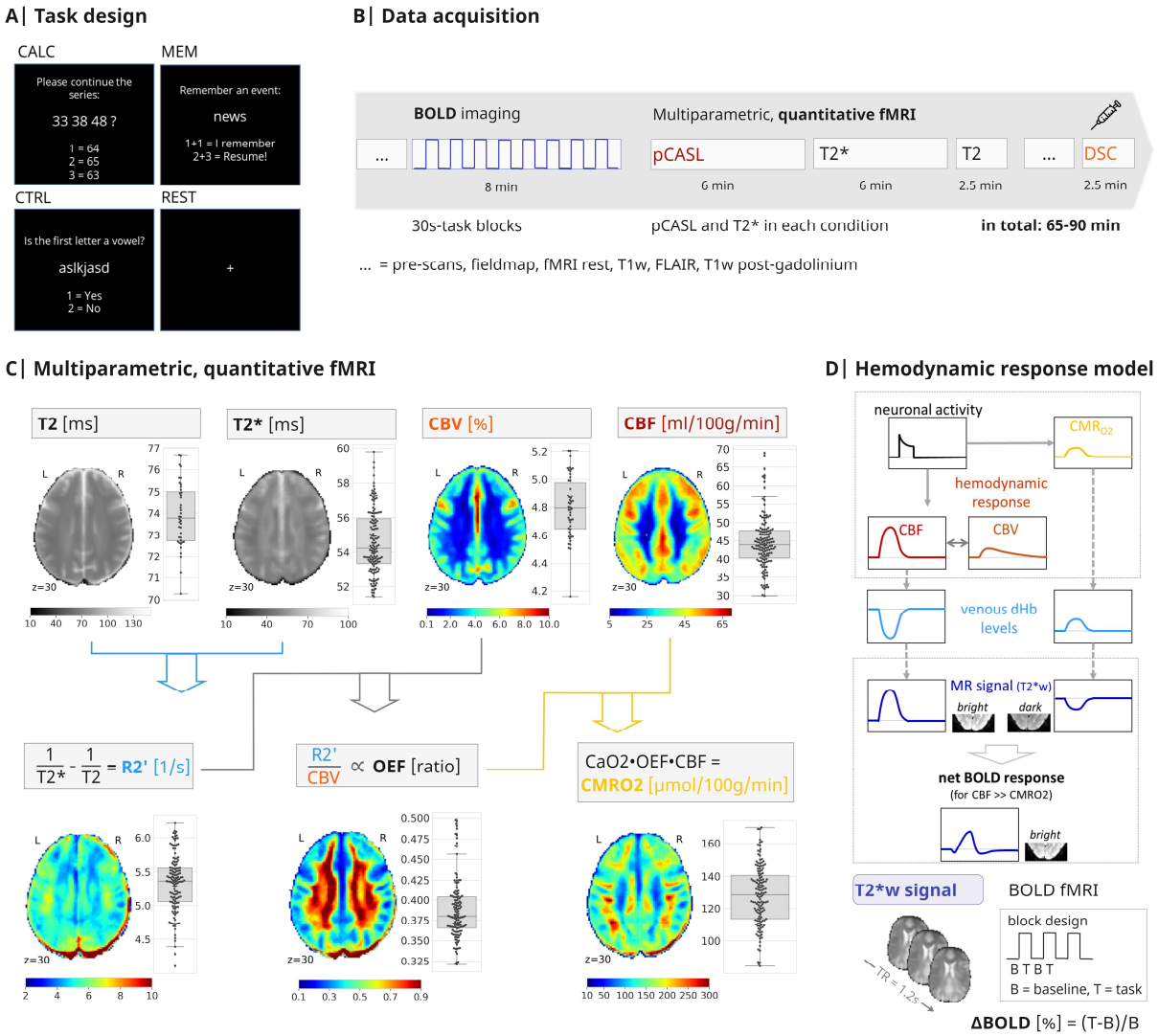

Figure 1. Study design, quantitative fMRI, and the hemodynamic response model of BOLD fMRI. A| We performed BOLD- and quantitative fMRI on healthy subjects performing four different conditions within the same imaging session: calculation task (CALC), autobiographical memory task (MEM), active control baseline (CTRL), and uncontrolled resting-state baseline (REST). **B|** During each imaging session, we acquired BOLD fMRI data with a 30-sec block design, together with multiparametric, quantitative BOLD (mqBOLD) data while conditions were presented in pseudo-randomized order: T2* mapping to measure both reversible and irreversible dephasing; pseudo-continuous arterial spin labeling (pCASL) to measure CBF during each condition; T2 mapping to once measure irreversible dephasing due to tissue properties; dynamic susceptibility contrast (DSC) MRI using a contrast agent to measure CBV during CTRL, at the end of the session. **C|** Quantitative fMRI delivers voxelwise CMRO2 by integrating T2, T2*, CBV, and CBF parameters via Fick's principle (see Methods section for detailed equations). Brain slices of subject-average parameter maps and boxplots illustrating average GM values (line, median; box limits, upper and lower quartiles; individual dots, subject average per condition). The reversible transverse relaxation rate (R2') reflects a voxel's overall deoxyhemoglobin (dHb) content. The OEF is proportional to R2'/CBV. Voxel-wise CMRO2 is then calculated as the product of OEF, CBF, and the arterial oxygen content of the blood (CaO2) as derived from individual measures of oxygen saturation and hematocrit. **D|** The canonical, hemodynamic response model of the BOLD signal: Increased neuronal activity leads to higher oxygen metabolism (CMRO2), decreasing oxygenation levels and increased dHb content in venous blood. Simultaneously, neurovascular coupling mechanisms

cause an increase in CBV and CBF. This hemodynamic response counteracts the effects of oxygen metabolism, leading to a total decrease in dHb content. In BOLD-fMRI, the net fluctuation of dHb levels is dynamically measured with T2*-weighted (T2*w) echo planar imaging (EPI). ΔBOLD during any task condition is calculated by subtracting task (T) from baseline (B) T2*w data. Based on this canonical model, positive ΔBOLD [%] is commonly interpreted as increased neuronal activity.

Negative BOLD signal responses do not necessarily indicate reduced oxygen metabolism

We conducted separate partial least squares (PLS) analyses on BOLD data, CBF-, and CMRO2 parameter maps to obtain statistically comparable results for BOLD and quantitative fMRI. These analyses yield bootstrap ratios (BSR), interpreted similarly to z-values (see Methods). Fig. 2A illustrates the cortical distribution of group-average ΔBOLD, ΔCBF, and ΔCMRO2 calculated in standard (MNI) brain space. We identified a widespread pattern of significant positive and negative ΔBOLD for the contrast CALC vs. CTRL, with negative ΔBOLD of a smaller amplitude than positive ΔBOLD. The histograms in Fig.2B illustrate the group-average parameter values within masks of significant ΔBOLD (group BOLD masks: CALC-positive, CALC-negative).

ΔCBF and ΔCMRO2 within the CALC-positive mask showed amplitudes typical for a canonical response: ΔBOLD[%] = 0.37%, ΔCBF[%] = 6.6%, ΔCMRO2[%] = 3.1%, *n*-ratio (ΔCBF[%] / ΔCMRO2[%]) = 2.1 (Fig. 2B). Within the CALC-negative mask, however, ΔCBF and ΔCMRO2 were much lower in amplitude with values around zero. To avoid image distortions that might occur during the normalization of subject data to MNI group space, we also analyzed data in native space using individual BOLD masks. This analysis revealed significant positive ΔCBF and ΔCMRO2 with overall higher signal amplitudes within the CALC-positive mask, but no significant hemodynamic response within CALC-negative masks (Fig. 2C). We also investigated the spatial patterns and amplitudes of CALC compared to the REST baseline (Fig. S1A), where we observed a stronger ΔBOLD in both directions than compared to CTRL (Fig. S1B). Again, ΔCBF and ΔCMRO2 significantly increased in CALC-positive masks but were not significantly different from zero in CALC-negative masks across subjects ($p > .001$) (Fig. S1B).

Overall, parameter values for positive ΔBOLD were in line with a canonical hemodynamic response, with ΔCBF (in %) being at least ten times higher than ΔBOLD and more than twice the amplitude of ΔCMRO2 (indicated by *n*-ratio of >2). However, we found no significant negative ΔCBF or ΔCMRO2 in the negative ΔBOLD masks across subjects.

We subsequently employed a region-specific analysis to investigate whether the absence of metabolic decreases was concealed by averaging parameter values across the CALC-negative mask. We identified eight clusters with positive ΔBOLD and nine with negative ΔBOLD (Fig. 2D, left). Within those clusters, the median ΔCMRO2 is significantly positive in four out of eight positive BOLD clusters but negative in none of the negative BOLD clusters (Fig. 2D, bar plots). The two clusters with negative ΔBOLD in the auditory network (SMN 1, SMN 2) even exhibit a significant positive ΔCMRO2. Within circumscribed regions, we thus identified an average discordant ΔBOLD in 50% of positive BOLD clusters and in 100% of negative BOLD clusters.

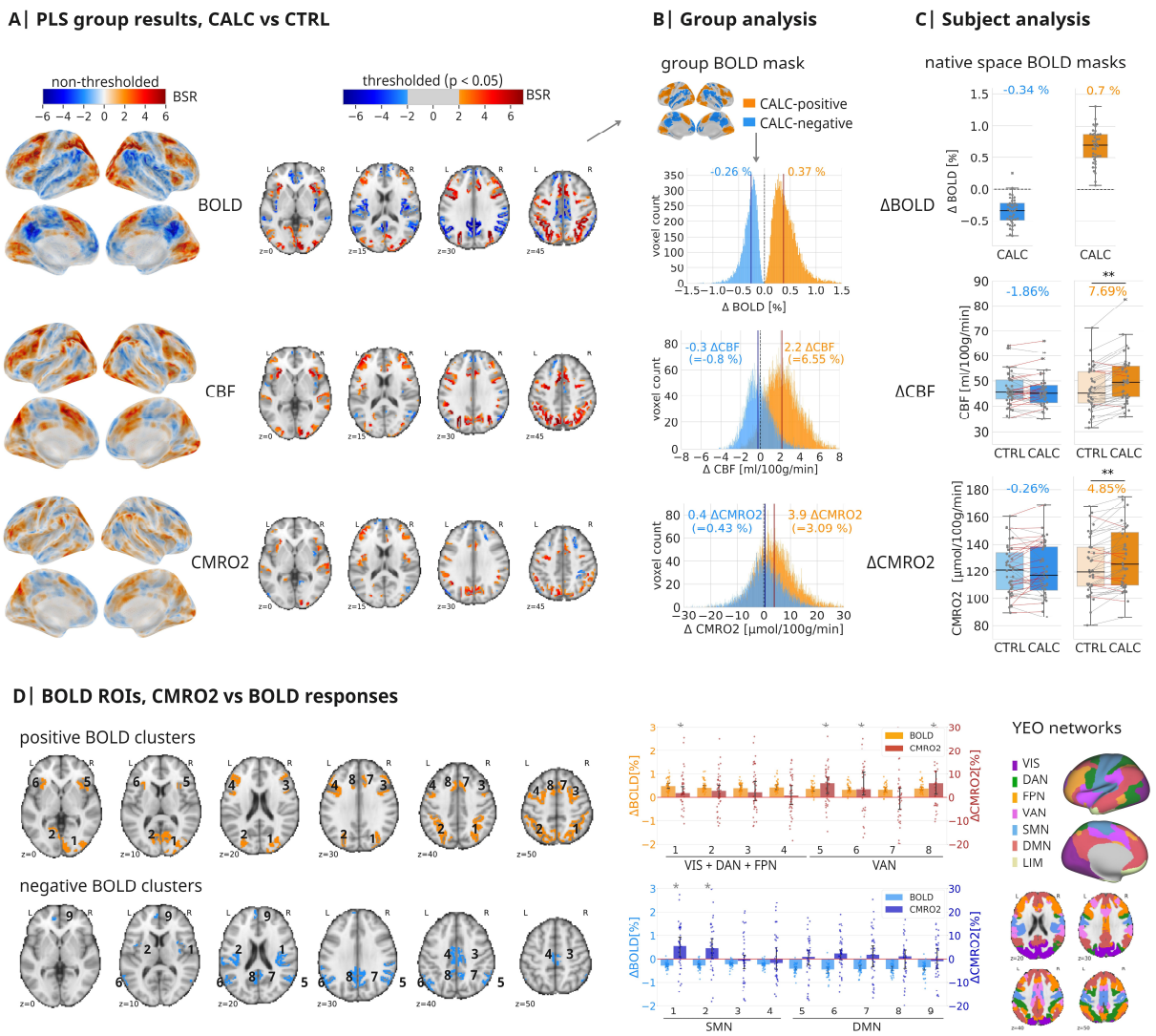

Figure 2. Negative BOLD signal changes do not necessarily indicate a reduction in oxygen metabolism. **A|** Statistical results of the PLS group analysis in standard MNI space, comparing CALC and CTRL, for both BOLD and quantitative fMRI parameter maps. Maps projected on the brain surface show non-thresholded bootstrap ratios (BSR, akin to z-values) of the first latent variable, which was significant in each analysis, i.e., for BOLD, CBF, and CMRO2 respectively (permutation tests, $p < .001$). Red voxels indicate higher values during CALC than during CTRL, while blue voxels represent the opposite contrast. Axial slices display significant brain clusters, thresholded at BSR ±2 (akin to $p < .05$, cluster size > 30 voxels) for the BOLD, CBF, and CMRO2 signals. **B|** Histograms depict group-average median voxel distributions of ΔBOLD, ΔCBF, and ΔCMRO2 (CALC minus CTRL) within the binarized CALC-positive and CALC-negative group masks (shown as surface plot). **C|** Subject distribution of ΔBOLD, ΔCBF, and ΔCMRO2 in native space. Dots represent subject values, calculated as the median across voxels within individual BOLD masks of significant positive (orange) and negative (blue) ΔBOLD. Paired samples, two-sided t-tests, ** $p < .001$. Gray lines connect values obtained from individual subjects, and red lines indicate subjects where the sign of ΔCBF or ΔCMRO2 deviates from the BOLD-indicated direction. **D|** Regional clusters (designated by numbers) of positive and negative ΔBOLD (PLS group results, thresholded at BSR > ±3) and associated bar plots showing ΔBOLD and ΔCMRO2. Please note the different axes for ΔBOLD versus ΔCMRO2. Bars indicate ΔBOLD[%] and ΔCMRO2[%] median across

voxels, error bars 95% CI, 2000 bootstraps, and dots represent subject values. Any signal increase or decrease where error bars cross the zero line is considered non-significant; an asterisk denotes $p < 0.05$. Clusters are located in different functional networks, as depicted on the brain surface and in axial slices (Thomas Yeo et al., 2011): visual (VIS); dorsal attention (DAN); frontoparietal (FPN); ventral attention (VAN); somatomotor (SMN); default mode (DMN) network.

There could be several reasons for the absence of hemodynamic and metabolic changes, particularly during negative ΔBOLD: i) voxel-specific characteristics or confounds of the MRI signal, ii) lower sensitivity of the imaging methods to detect negative ΔCBF or ΔCMRO2 of smaller amplitudes, or iii) different hemodynamic mechanisms in specific voxels or regions. In the following, we will explore each of these potential explanations.

First, we analyzed ΔBOLD and ΔCMRO2 for the MEM contrast (Fig. S1C). Across all voxels of the MEM-positive and MEM-negative masks (Fig. S1D) and also on the subject level (Fig. S1F), we found similar BOLD signal amplitudes as for the CALC condition, again with stronger positive than negative ΔBOLD. When analyzing the quantitative data, we observed significant positive ΔCBF and ΔCMRO2 in the MEM-positive mask but no significant changes in the MEM-negative mask. This suggests that, on average, and across different task conditions, positive ΔBOLD indicates significant positive ΔCMRO2, but the metabolic interpretation of negative ΔBOLD is less clear.

Most voxels with positive ΔBOLD during MEM were found within the default mode network (DMN), where we had already identified negative ΔBOLD during CALC (Fig. S1E). As a control analysis for voxel-specific characteristics that might alter the sensitivity to detect hemodynamic responses, the overlap between MEM-positive and CALC-negative masks allowed us to study CBF and CMRO2 responses for positive and negative ΔBOLD within the same voxels. Fig. S1G shows the histograms of ΔBOLD, ΔCBF, and ΔCMRO2 for all voxels of a conjunction mask (MEM-positive ∧ CALC-negative). On average, we found a canonical hemodynamic response for positive ΔBOLD (0.32%) caused by a substantial increase in ΔCBF (5.94%) and a positive ΔCMRO2 (3.54%). However, for negative ΔBOLD (-0.29%), the ΔCBF (-0.47%) was much weaker than expected within the canonical framework, i.e., for a negative response of similar magnitude to the positive response within the same voxels. Thus, the low ΔCBF during a positive ΔCMRO2 results in a negative ΔBOLD.

A summary of subject-average changes for all parameters and all task contrasts is presented in Table 2. Altogether, we found a consistent relationship for positive ΔBOLD-ΔCMRO2, yet with regional variability (Fig. 2D). Crucially, the discrepant results for positive and negative ΔBOLD within 'conjunction voxels' (Fig. S1G) indicate that the absence of a canonical hemodynamic response for negative ΔBOLD cannot be explained by voxel characteristics such as vascular composition or reactivity, as the same voxels show a canonical hemodynamic response for positive ΔBOLD.

Table 2

Mean BOLD signal change and parameter values of the mqBOLD approach across subjects (standard deviation) within individual BOLD-fMRI masks, separately for positive and negative BOLD responses.

task baseline	BOLD mask	BOLD [%]	CBF [ml/100g/min]		CMRO2 [µmol/100g/min]		OEF [ratio]	
			baseline	ΔCBF	baseline	ΔCMRO2	baseline	ΔOEF
CALC CTRL	CALC-pos	**0.70%**	46.5 (8.2)	**7.7%** 3.1** (3.2)	124.0 (20.9)	**4.9%** 6.4** (7.7)	0.37 (0.06)	**-3.2%** -0.013** (0.01)
	CALC-neg	**-0.34%**	46.6 (6.4)	-1.9% n.s.	120.1(18.1)	-0.3% n.s.	0.35 (0.05)	0.01% n.s.
MEM CTRL	MEM-pos	**0.51%**	48.5 (9.1)	**5.6%** 2.6** (2.8)	125.0 (18.8)	**5.1%** 6.4** (8.2)	0.36 (0.06)	**-0.7%** -0.003* (0.013)
	MEM-neg	**-0.35%**	48.4 (8.9)	-1.7% n.s.	126.7 (31.1)	-1.1% n.s.	0.36 (0.07)	1.1% n.s.
CALC REST	CALC-pos	**1.01%**	45.3 (8.8)	**10.0%** 4.4** (3.2)	123.5 (24.5)	**6.4%** 6.5** (8.1)	0.38 (0.06)	**-3.6%** -0.014** (-0.014)
	CALC-neg	**-0.38%**	47.7 (7.8)	**-2.6%** -1.2 (3.6)	123.7 (20.3)	-0.9% n.s.	0.36 (0.06)	1.0% n.s.

Note. Quantitative values (black font) of CBF, CMRO2, and OEF are displayed both at baseline and as absolute delta values (task minus baseline), along with percent change values (colored) for each contrast. Values reflect data as displayed in Fig. 2C, with CMRO2 values in CALC being corrected for CBV increases, see Methods. ** $p < .001$, based on paired, two-sided t-tests, $df = 39$ for CALC vs. CTRL contrasts, $df = 29$ for CALC vs. REST and MEM vs. CTRL contrasts.

Control analyses

According to the hemodynamic response model (Fig. 1D), changes in CBF are the main contributor to the neurovascular coupling mechanism. Therefore, we performed several control analyses to validate the sensitivity of pCASL imaging to detect ΔCBF (Fig. S2).

We identified magnitudes of ΔCBF ranging from -12% to +29%, and regions with positive ΔCBF exhibited a higher *n*-ratio than regions with negative ΔCBF (Fig. S2A). Moreover, our pattern of negative ΔCBF during CALC corresponds to the localization of negative ΔCBF observed with PET (Fig. S2B). Notably, areas showing significant CBF decreases from PET and MRI data are spatially less widespread than those with BOLD signal decreases (Fig. S2B, group PLS results) and predominantly centered around peak regions, as shown in Fig. S2A. Additionally, the homogeneity of OEF across GM is similar to that derived from PET imaging (Fig. S2C).

Subsequently, we evaluated the stability of BOLD and CBF signals across continuous task performance. In the main study (Fig. 1), block durations vary for BOLD (30 sec) and quantitative (approx. 6 min) fMRI to achieve the best signal-to-noise ratio (SNR) for each modality. To investigate signal stability across more extended periods of task performance, we collected BOLD fMRI data in a separate control study (N=18) while participants continuously performed the CALC and MEM tasks during 3-minute task blocks. Fig. S2C demonstrates that the BOLD

signal remains constant throughout task performance, suggesting no evidence for habituation or drift effects. Additionally, the average amplitudes of ΔBOLD in the control study were similar to those observed in our main study (ΔBOLD[%] CALC-positive/CALC-negative/MEM-positive: 0.6/-0.46/0.34; main study: 0.70/-0.34/0.51). Finally, the time-resolved analysis of CBF from the main study shows that the signal remained constant throughout the entire measurement blocks (Fig. S2D).

Empirical validation of the Davis model explaining concordant and discordant BOLD signal responses

In the following section, we evaluate the consistency of discordant ΔBOLD-ΔCMRO2 relationships on the voxel level and compare our empirical data to an established model of hemodynamic responses. The Davis model (Davis et al., 1998) predicts the extent of BOLD responses for a realistic range of ΔCMRO2[%] and ΔCBF[%] across the cortex. Fig. 3A displays the model's prediction of ΔBOLD (contours, -3% to +3%) for a set of typical hemodynamic response parameters. The model illustrates that a canonical BOLD signal response emerges when ΔCBF exceeds ΔCMRO2, with ΔBOLD, ΔCBF, and ΔCMRO2 all changing in the same direction. In other terms, a positive ΔBOLD emerges for a *n*-ratio > 1. However, the model also indicates that ΔBOLD may conflict with the actual metabolic changes if ΔCBF is lower than ΔCMRO2 (i.e., for an *n*-ratio <1) or if ΔCBF and ΔCMRO2 have opposite signs. These areas of discordance between ΔBOLD and ΔCMRO2 are highlighted by violet shadings in Fig. 3A. For instance, a negative ΔBOLD of -1.3% would be measured if CBF increases by only about 5% during a ΔCMRO2 of +20%. In other words, an identical metabolic change can result in opposite signs of the BOLD signal, depending on the extent of ΔCBF. Since we have measured ΔBOLD, ΔCBF, and ΔCMRO2, our data are well-suited to assess the consistency of the Davis model with empirical data. Importantly, we calculate voxel CMRO2 from our imaging data using Fick's principle and then compare these parameters to independent predictions from the Davis model.

Fig. 3B shows subject-average data of ΔCBF versus ΔCMRO2 for CALC vs. CTRL, with colors indicating positive or negative ΔBOLD, across all GM voxels of the cortex (see also Fig. S3A for CALC vs. REST, and Fig. S4A for MEM vs. CTRL). To address issues with SNR when integrating all imaging modalities at the voxel level, we used semi-quantitative calculations of CMRO2 (see Methods and Fig. S5 for a sensitivity analysis). Our experimental data support several predictions of the Davis model. Overall, voxels exhibiting positive and negative ΔBOLD are located above and below a straight line with a slope of 1, indicating a *n*-ratio of around 1. Importantly, our data also confirm the existence of a significant number of voxels with ΔBOLD opposite to their metabolic response, which we termed discordant responses. Such discordant responses are represented by red voxels on the left and blue voxels on the right side of zero ΔCMRO2 (Fig. 1B, red dashed line). Essentially, discordant voxels exhibit positive ΔBOLD despite negative ΔCMRO2 and vice versa. Importantly, if we were to interpret the activity in

those voxels based solely on BOLD fMRI data and assuming a canonical hemodynamic response across the entire cortex, the activity in those voxels would be misinterpreted.

To provide a more precise illustration of the location of discordant voxels, we split the data from Fig. 3B into two distinct scatter plots for CALC-positive (top) and CALC-negative (bottom) contrasts only (Fig. 3C). In both plots, voxels with discordant ΔBOLD compared to ΔCMRO2 were highlighted by violet shading. The total number of discordant voxels amounts to 31% and 66% for positive and negative ΔBOLD, respectively (Fig. 3C, pie charts). The second pie chart in the lower scatter plot demonstrates a similar ratio of discordant voxels when only including negative ΔBOLD voxels within the DMN, the network with the most consistently reported negative BOLD signal responses. Furthermore, the brain slices demonstrate that discordant voxels are spatially distributed across the cortex (Fig. 3C, spatial distribution). The stacked bar plots reveal that discordant voxels are equally distributed among voxels with the lowest to highest quartile of BOLD signal amplitudes (Fig. 3C, BOLD amplitude distribution, q1 represents the lowest quartile and q4 represents the highest quartile of BOLD signal amplitudes).

We also performed the same analyses for the CALC vs. REST (Fig. S3B) and MEM vs. CTRL (Fig. S4B) contrasts. We likewise observed the presence of discordant voxels across the entire range of ΔBOLD. Specifically, discordant voxels accounted for 36%/52% of significant positive/negative ΔBOLD voxels in the CALC vs. REST contrast and for 12%/54% in the MEM vs. CTRL contrast. Again, discordant voxels were distributed throughout the entire cortex.

Fig. 3D summarizes the distribution of subject-median parameter values across concordant and discordant voxels. ΔBOLD in concordant voxels (Fig. 3D, yellow/turquoise bars) is consistent with the canonical hemodynamic response model with a median *n*-ratio (ΔCBF/ΔCMRO2 per voxel) of 2.0 and 1.6 across concordant positive and negative ΔBOLD, respectively. However, a considerable number of discordant voxels (Fig. 3D, violet bars) show ΔBOLD opposite to their metabolic response and a lower ΔCBF than expected by the canonical model. Importantly, discordant ΔBOLD occurs in one-third of voxels with positive ΔBOLD and in two-thirds of voxels with negative ΔBOLD and across different task conditions. Moreover, discordant voxels are uniformly dispersed throughout the cortex and arise within all ranges of ΔBOLD magnitudes.

The discordance between ΔBOLD and ΔCMRO2 might emerge from partial volume effects when integrating voxel data from imaging sequences with heterogeneous voxel sizes, as in our main study. We thus performed a replication study (N=10) using the identical task design (CALC vs. CTRL) and analysis pipeline of the main study yet with adjusted MRI sequences to achieve fully harmonized voxel matrices across all parameter maps of BOLD and mqBOLD data (see Methods section). The results of the replication study were fully consistent with those of the main study (Fig. S6). We found that 40% of all voxels with either significant positive or negative ΔBOLD were classified as discordant. As in the main study, discordant voxels showed smaller CBF responses than expected from the hemodynamic response model.

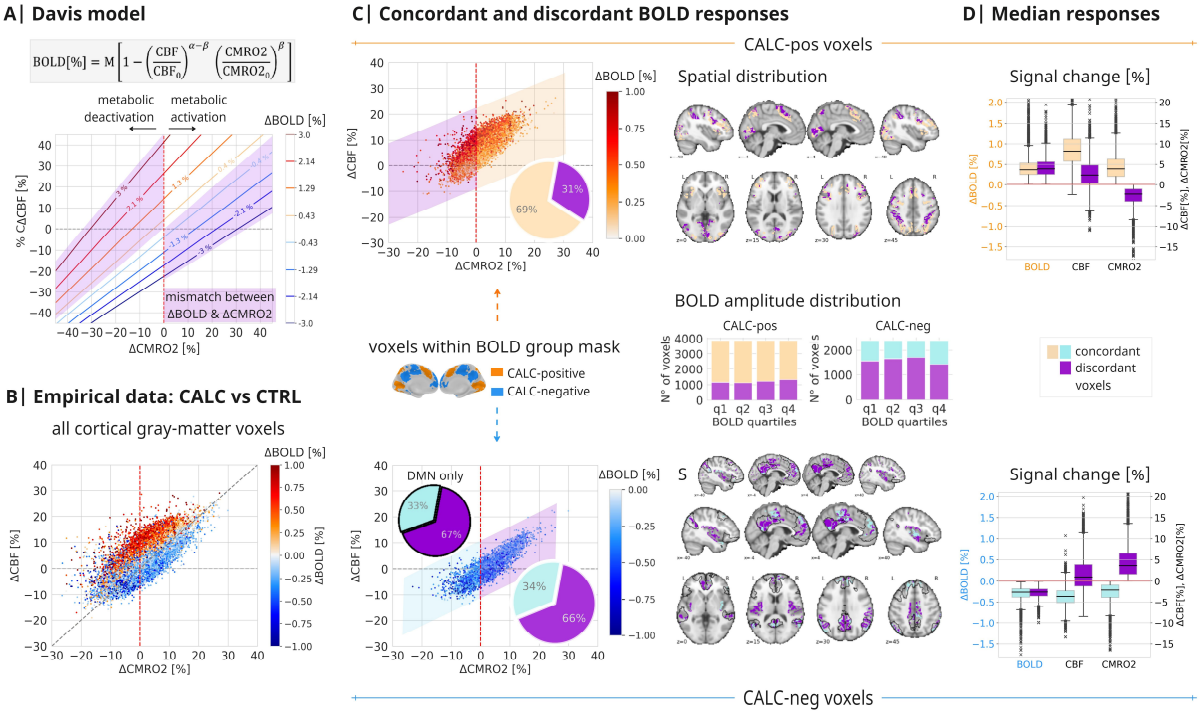

Figure 3. Dependence of BOLD responses on changes in CBF and CMRO2. A| Visualization of the Davis model. Predicted BOLD responses (ΔBOLD[%]) are depicted as colored contour lines across ΔCBF[%] and ΔCMRO2[%]. The model illustrates that, for a given ΔCMRO2[%], the sign and amplitude of the BOLD response depend on the amplitudes of ΔCBF[%]. The canonical hemodynamic response model requires that ΔCBF surpasses ΔCMRO2, resulting in a positive ΔBOLD and vice versa for negative BOLD signal changes. However, the Davis model also predicts a range of BOLD responses with discordant signs compared to the change in underlying metabolic activity (violet shading). **B|** Empirical data from BOLD- and quantitative fMRI for all cortical voxels. ΔCMRO2 was calculated from semi-quantitative data (see Methods), median across all subjects per voxel, with colors indicating ΔBOLD[%]. Our experimental data replicate the slope and range of values as predicted by the Davis model, particularly demonstrating a substantial number of voxels with ΔBOLD opposing ΔCMRO2. **C|** Voxels with significantly positive (top) and negative (bottom) BOLD responses from (B) are plotted separately here. Voxels with ΔBOLD concordant to ΔCMRO2 are depicted on a pale (yellow/turquoise) background, while voxels with discordant ΔBOLD are shown on a violet background. The pie plots summarize the ratio of discordant to concordant voxels. In the lower panel, the pie plot with black contours summarizes the ratio of discordant voxels within only the DMN. Axial slices illustrate the spatial distribution of significantly concordant and discordant BOLD voxels, with black contours indicating the DMN. The stacked bars in the right center depict the amplitude distribution of discordant and concordant voxels across BOLD amplitude quartiles. It is noteworthy that discordant voxels show neither spatial nor amplitude preference. **D|** The boxplots summarize ΔCMRO2[%] and ΔCBF[%] across all voxels with either concordant or discordant ΔBOLD[%]; line, median; box limits, upper and lower quartiles. Please note that discordant and concordant voxels feature a similar ΔBOLD amplitude distribution despite indicating opposite metabolic responses.

Consistency of concordant or discordant BOLD signal responses depends on baseline OEF

In the following section, we used the conjunction mask from the CBF control analysis above (voxels with both positive and negative BOLD responses during either CALC or MEM) to investigate whether these voxels show a consistent hemodynamic response pattern from negative to positive ΔBOLD. We categorized each voxel based on whether it either showed consistent concordant ('concordant only') or discordant ('discordant only') ΔBOLD in both tasks or if it displayed a mixed response ('mixed' voxels), i.e., a concordant BOLD signal response in one condition but a discordant one in the other task (Fig. 4A). The pie chart displays that the majority of voxels (48%) showed a mixed response. In contrast, 18% and 35% consistently showed a discordant and concordant response, respectively. Fig. 4B shows the spatial and amplitude distributions of ΔCBF and ΔCMRO2 in relation to ΔBOLD for each of the three voxel types. The 'concordant only' voxels show a canonical hemodynamic response with an *n*-ratio of around two, independent of the task condition or the sign of the BOLD signal response (Fig. 4B, yellow/turquoise bars). In contrast, 'discordant only' voxels lack a canonical hemodynamic response for either direction of ΔBOLD (Fig. 4B, violet/lilac). The 'mixed' voxels (Fig. 4B, red/orange) show a canonical hemodynamic response with a surplus of ΔCBF for positive ΔBOLD but lack a significant ΔCBF for negative ΔBOLD.

As changes in CMRO2 without an adequate CBF response can only be accommodated via OEF, we tested whether the three types of voxels differ in their OEF during baseline. We speculated that 'discordant only' voxels, with the lowest ΔCBF during a task, would have the lowest baseline OEF (indicating the highest oxygen buffer). In line with this hypothesis, we found that baseline OEF was gradually lower from 'concordant only' through 'mixed' to 'discordant only' voxels (Fig. 4C). Together, this suggests that 'discordant only' voxels have a sufficient oxygen buffer to accommodate changes in oxygen demand via ΔOEF. In contrast, voxels with a high baseline OEF need to regulate additional oxygen demand via CBF. Please note that OEF was acquired independently from CBF data using the mqBOLD approach.

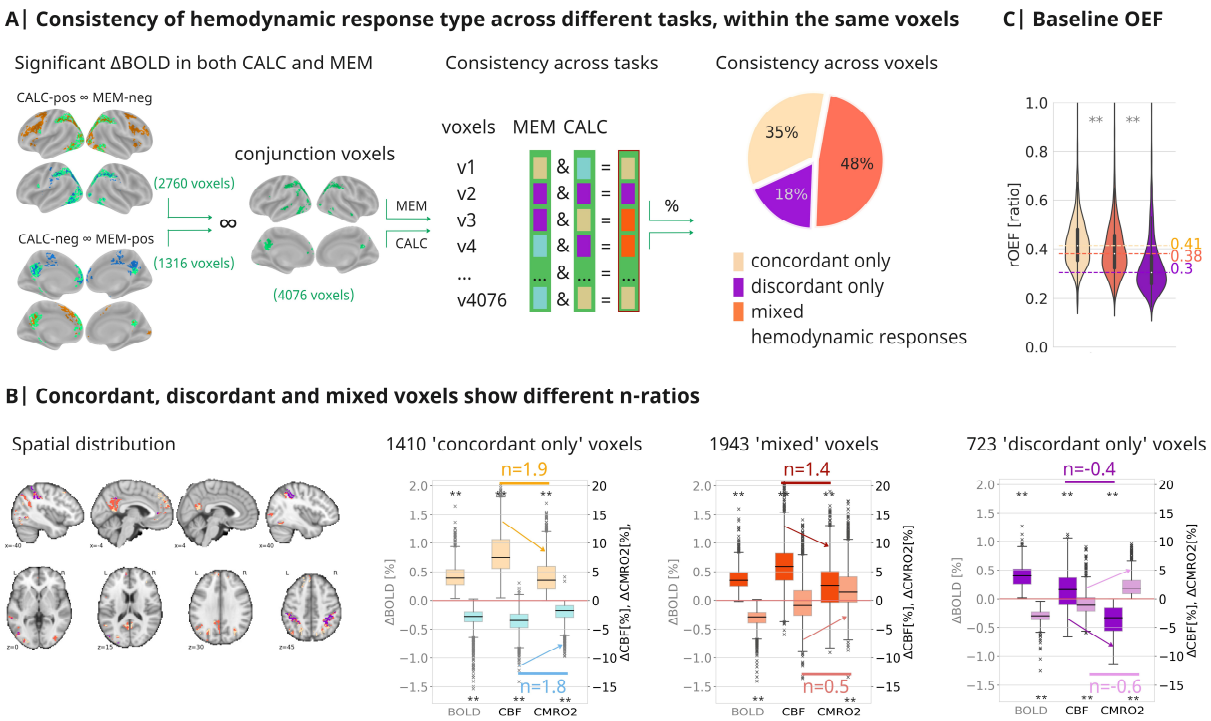

Figure 4. Concordant or discordant BOLD signal responses depend on baseline OEF. A| Conjunction voxels (green outlines) – showing positive and negative BOLD signal changes during either CALC or MEM – were sorted according to their response type. The pie chart summarizes the consistency of response types across voxels: 35% of all conjunction voxels showed concordant responses (same sign of ΔBOLD and ΔCMRO2) during both MEM and CALC conditions ('concordant only'). 18% of all conjunction voxels showed discordant responses in both conditions ('discordant only'). 48% of the conjunction voxels ('mixed' voxels) showed concordant responses in one condition but discordant responses in the other. **B|** Spatial distribution is depicted on brain slices using consistent color overlays: 'Concordant only' and 'mixed' voxels mainly cluster in regions of the DMN, while 'discordant only' voxels occur in the medial part of the VAN. The boxplots illustrate subject-median parameter values separately for 'concordant only,' 'mixed,' and 'discordant only' voxels. While the range of ΔBOLD is similar across the three groups, ΔCBF and ΔCMRO2 vary strongly as expressed by their *n*-ratios. Asterisks indicate significant differences from zero, tested via independent t-tests corrected for multiple comparisons. **C|** The three voxel groups exhibit significantly different OEF during CTRL baseline, with 'concordant only' voxels having significantly higher OEF and 'discordant only' voxels having significantly lower OEF than 'mixed' voxels. ** $p < 0.001$, independent sample permutation test on the median values, conducted for 'mixed' versus the two other voxel types, 2000 permutations.

Baseline OEF relates to different hemodynamic response types

We then investigated the baseline hemodynamics across the entire cortex. We pooled all voxels with significant ΔBOLD during either task (CALC, MEM), which accounted for 53% of all GM voxels, and grouped them into voxels of concordant ΔBOLD, discordant ΔBOLD, and remaining GM voxels not involved in any task (Fig. 5A, pie chart). We then analyzed the relationship between baseline CMRO2 and CBF, OEF, and CBV and found a significant linear correlation between CMRO2 and all three hemodynamic parameters, consistent across all voxels (Fig. 5A).

Next, we used multiple linear regression to assess the individual contribution of baseline OEF, CBF, or CBV to the variance of baseline CMRO2 across concordant and discordant voxels. The model was significant, with similar model parameters for each group (concordant model: $F(3,21809) = 72070$, $p < .001$, CMRO2 = 139.9 + 321.1*OEF + 3.3*CBF + 0.4*CBV + e, R^2=0.91; discordant model: $F(3,14544) = 48390$, $p < .001$, CMRO2 = 128.1 + 309.2*OEF + 3.2*CBF + 1.3*CBV + e; R^2=0.91; all predictors mean-centered, p<.001 for all beta values). In summary, baseline OEF consistently accounts for >68% of CMRO2 variability across concordant and discordant voxels, followed by CBF (>28%) and CBV (>1%). Notably, discordant voxels also have a lower baseline metabolism than concordant voxels, as indicated by the parameter values of CMRO2. We then assessed whether concordant and discordant voxels differ in their average baseline levels of CBF, OEF, and CBV. Across subjects, concordant voxels show significantly higher CBF, lower OEF, and higher CBV than discordant voxels during baseline (Fig. 5B).

To independently support our finding of lower OEF and higher CBV in discordant voxels, we used two external quantitative susceptibility mapping (QSM) datasets of the human brain (Fig. 5C). We projected our masks of concordant and discordant voxels onto these high-resolution data and tested for differences between the two groups of voxels. We observed similar susceptibility values among concordant and discordant voxels, yet a slightly but significantly lower median for discordant voxels (Fig. 5C, top) in the first dataset (Huck et al., 2019). This indicates a lower dHB content and aligns with the lower OEF we observed in our data. Moreover, we found a significantly higher venous density for discordant voxels (Fig. 5C, bottom) in the second dataset (Lüsebrink et al., 2021), which was also in line with the higher CBV values we observed in our data.

In the final step, we asked whether ΔOEF is an alternative mechanism to ΔCBF in modulating oxygen demand during task processing. We used multiple linear regression to assess the individual contributions of ΔCBF and ΔOEF to the variance of ΔCMRO2 across all task conditions. We identified two distinct patterns of hemodynamic responses for concordant and discordant voxels (Fig. 5D). In concordant voxels, ΔCMRO2 is primarily modulated by ΔCBF: $F(2,21971) = 67980$, $p < .001$, with ΔCBF explaining 87% and ΔOEF 16% of a total explained variance of R^2=0.86 of the model (ΔCMRO2[%] = 2.6 + 0.83*ΔOEF[%] + 0.86*ΔCBF[%] + e; all predictors mean-centered, p<.001 for all beta values). In contrast, discordant voxels exhibit a different hemodynamic response, where ΔCMRO2 is primarily modulated by ΔOEF: $F(2,14694) = 39320$, $p < .001$, with ΔOEF explaining 58% and ΔCBF 42% of a total explained variance of R^2=0.84 of the model (ΔCMRO2[%] = 1.2 + 1.1*ΔOEF[%] + 0.88*ΔCBF[%] + e; all predictors mean-centered, p<.001 for all beta values). As expected from the canonical hemodynamic response, concordant voxels regulate ΔCMRO2 primarily via ΔCBF (87%), while discordant voxels predominantly regulate their oxygen demand via ΔOEF (58%) and only secondary via ΔCBF (42%). As empirical ΔCBV only exists for the CALC-CTRL contrast, we couldn't include it in these regression models. Furthermore, it should be noted that the negative correlation between ΔCMRO2 and ΔOEF for concordant voxels (Fig. 5D, middle plot) results from the compensatory rise in oxygenation levels during the surplus of ΔCBF.

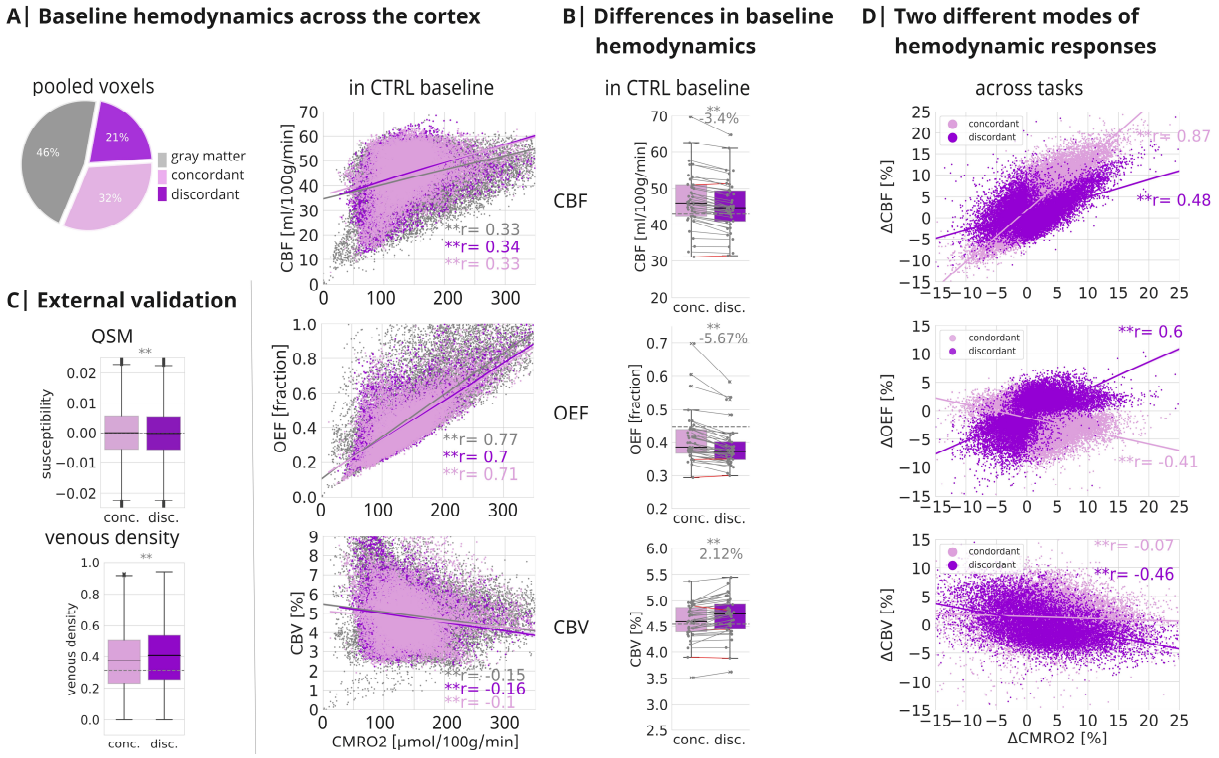

Figure 5. Two types of hemodynamic responses via changes in CBF or OEF. A| Across all task conditions, 21% of all GM voxels showed discordant, 32% showed concordant responses, and 48% were not significantly involved in any task. Regression plots: During baseline, CMRO2 and CBF show a medium correlation (Pearson's $r > 0.32$, $p < .001$), CMRO2 and OEF are highly correlated ($r > 0.7$, $p < .001$), and CMRO2 and CBV show a weak negative correlation ($r < -0.1$, $p < 0.001$) across all groups of voxels. **B|** Across subjects, discordant (disc.) voxels, on average, show significantly lower CBF (-3.4%), OEF (-5.7%), and higher CBV (2.1%) than concordant (conc.) voxels (paired-samples, two-sided t-test, $p < .001$). Boxplots: line, median; box limits, upper and lower quartiles; gray line, median of remaining GM voxels. **C|** Marginally, but significantly lower baseline susceptibility (QSM) and higher venous density in discordant vs. concordant voxels, revealed by two external datasets (Huck et al., 2019; Lüsebrink et al., 2021). Boxplots: line, median; box limits, upper and lower quartiles; gray line, median of remaining GM voxels. ** $p < .001$, independent samples permutation test on the median values, conducted for discordant versus concordant voxels, 2000 permutations. **D|** Correlation of ΔCMRO2[%] with either ΔCBF[%], ΔOEF[%], or ΔCBV[%] across all task contrasts (CALC or MEM vs. CTRL), separately for concordant (pale) and discordant (dark violet) voxels. ΔCMRO2 and ΔCBF showed a strong positive correlation across concordant voxels ($r = .87$, $p < 0.001$) and a moderate correlation across discordant voxels ($r = .48$, $p < .001$). In contrast, ΔCMRO2 and ΔOEF showed a moderate, positive correlation across discordant voxels ($r = .60$, $p < .001$) and a weak, negative correlation across concordant voxels ($r = -.41$, $p < .001$). ΔCBV could only be evaluated for a subset of 10 subjects and only across the CALC vs. CTRL contrast, see Methods. ΔCMRO2 and ΔCBV across this subset showed a weak correlation around zero across concordant voxels ($r = -.07$) and a moderate, negative correlation across discordant voxels ($r = -.46$, $p < 0.001$).

DISCUSSION

In this study, we examined the consistent presence of a canonical hemodynamic response across GM voxels throughout the human cortex. Such a finding would provide crucial evidence for the common interpretation of positive and negative ΔBOLD as indicators of increased or decreased neuronal activity. Surprisingly, our results show that around 40% of brain voxels with significant BOLD signal changes, measured during different task conditions, displayed discordant changes in oxygen metabolism. Specifically, discordant voxels with positive ΔBOLD showed a decrease in ΔCMRO2, while those with negative ΔBOLD had an increase in ΔCMRO2. By measuring changes in BOLD signal, CBF, OEF, and CMRO2 within the same imaging session, we identified a different type of hemodynamic response as an explanation. Discordant voxels regulate changes in oxygen demand primarily via ΔOEF, while concordant voxels show a surplus of ΔCBF, as predicted by the canonical hemodynamic response model. Additionally, we found lower baseline CMRO2 and OEF in discordant voxels, suggesting that their baseline oxygen supply is sufficient to meet changes in metabolic demand. In conclusion, we have identified two types of hemodynamic responses to changes in neuronal activity, which seem to depend on baseline OEF and metabolism.

Average BOLD and mqBOLD signals suggest a canonical hemodynamic response for positive ΔBOLD

In this study, we combined BOLD- with mqBOLD fMRI to investigate hemodynamic and metabolic changes in relation to BOLD signal changes. Participants performed cognitive tasks eliciting both positive and negative BOLD signal responses across the cortex. Specifically, we aimed to elicit both response types within the same voxels, allowing us to directly compare their hemodynamic responses. To this end, we employed a cognitively demanding calculation task that induces positive ΔBOLD in somatosensory, frontoparietal, and ventral- and dorsal attention regions (Amalric & Dehaene, 2016; Fehr et al., 2007; Lin et al., 2011a) while simultaneously causing negative ΔBOLD in regions of the DMN (Anticevic et al., 2012; Raichle et al., 2001; Shulman, FIEZ, et al., 1997; Smallwood et al., 2021). Additionally, participants engaged in an autobiographical memory task known to induce positive ΔBOLD in regions of the DMN, partly overlapping with those of negative ΔBOLD during CALC (Andrews-Hanna et al., 2014; Davey et al., 2016; Ino et al., 2011; Spreng & Grady, 2010).

We also considered the issue of different baseline states in our study. The BOLD signal response to cognitive tasks is usually compared to low-level control tasks as the baseline condition (Addis et al., 2007; Burianova et al., 2010; Burianova & Grady, 2007a; DuPre et al., 2016; Spreng et al., 2010; Spreng & Grady, 2010). Studies showing negative ΔBOLD, however, typically compare against an experimentally uncontrolled resting state (Anticevic et al., 2012; Lin et al., 2011a; Pfefferbaum et al., 2011; Raichle et al., 2001; Singh & Fawcett, 2008). Hence, we included both types of baseline conditions in our study. All our task conditions elicited BOLD signal responses as expected. Averaged across voxels, negative BOLD signal responses were

about 50-70% of the amplitude of positive ΔBOLD (Fig. 2). Moreover, we found that ΔBOLD was larger when compared to REST than to CTRL baseline (Table 2, Fig. S3).

Compared to BOLD fMRI, which requires subtraction analyses between conditions, the mqBOLD approach delivers quantitative measures for each condition. During CTRL baseline, we observed average GM values of CMRO2 and hemodynamic parameters (see Table 1) as previously reported for the healthy human brain (Aoe et al., 2018; Cho et al., 2018; Gauthier & Hoge, 2012; Ito et al., 2021; Lee & Wehrli, 2022; Leontiev & Buxton, 2007; Liang et al., 2013; Raichle et al., 2001; Stone & Blockley, 2017; Wise et al., 2013; J. Zhang et al., 2015, 2015). Similarly, task-related changes (see Table 2) aligned with previous results (Gauthier et al., 2012; Restom et al., 2008; Y. Zhang et al., 2021). Analyzing mqBOLD data in relation to positive ΔBOLD, we found a concordant relationship between average BOLD signal changes and the quantitative parameters, fitting a canonical hemodynamic response (DiNuzzo et al., 2023; Uludağ et al., 2004), with ΔCBF surpassing ΔBOLD by a factor of 10-20, a *n*-ratio of around 2, and ΔCMRO2 being approximately ten times higher than ΔBOLD across subjects (Fig. 2).

Discordant hemodynamic responses for regions with positive ΔBOLD and overall for negative ΔBOLD

Despite evidence for a canonical hemodynamic response for the average of positive ΔBOLD, we did not find any significant hemodynamic or metabolic changes for the average of negative ΔBOLD across subjects (see Fig. 2 C) for either task condition (see Fig. S1 F), or when comparing against CTRL or REST baseline (see Fig. S1 B). In a region-specific analysis, we even observed significant deviations from the canonical response model in clusters with positive ΔBOLD. On average, we identified non-significant ΔCMRO2 in four out of eight clusters with positive ΔBOLD and in all nine clusters with negative ΔBOLD (Figs. 2D). One could argue that voxels with discordant ΔBOLD might suffer from voxel-specific artifacts such as partial volume effects or sparse vasculature, thereby lacking a significant ΔCBF. To address this issue, we designed our study to achieve significant ΔBOLD during both CALC and MEM tasks in identical voxels, which allows the within-voxel comparisons of ΔBOLD and quantitative parameters. Across only these voxels (Fig. S1G, 'conjunction voxels'), we again observed only weak ΔCBF (-0.5%) for negative ΔBOLD, but a strong positive ΔCBF (5.9%) for positive ΔBOLD, despite comparable positive and negative ΔBOLD amplitudes (-0.29% and 0.32%). At least for this subset of voxels, a discordant negative ΔBOLD is unlikely caused by voxel-specific artifacts, as we did observe a canonical hemodynamic response for positive but not negative BOLD signal changes.

In summary, we identified a canonical hemodynamic response for positive ΔBOLD across the cortex, yet with specific regions displaying a discordant BOLD signal response. For negative ΔBOLD, we did not find any significant ΔCBF or ΔCMRO2. Our findings across regions of the human cortex match earlier studies in animals that reported inconsistent hemodynamic responses in cortical compared to subcortical regions (Huo et al., 2014; Shaw et al., 2021; Shih et al., 2011).

Validation of discordant hemodynamic responses with an established hemodynamic response model, in a replication study, and within the same voxels

On the level of voxels, we evaluated our findings in comparison to a well-established model of cerebral hemodynamic responses (Fig. 3). The Davis model predicts the amplitude and trajectories of BOLD signal changes for realistic ΔCMRO2 and associated ΔCBF in the human brain (Davis et al., 1998). Although published about two decades ago, no study has examined the model's accuracy across the human cortex using BOLD fMRI and quantitative fMRI data. Intriguingly, the Davis model predicts a range of discordant positive and negative ΔBOLD for biologically plausible ΔCBF in relation to ΔCMRO2 (Fig. 3, violet shadings and voxels). Our empirical data (Fig. 3B) closely align with the predictions of the Davis model. Across all voxels with concordant positive and negative ΔBOLD, we found a canonical hemodynamic response with an average *n*-ratio of 2.0 and 1.6, respectively (Fig. 3D). Importantly, our data also confirm the occurrence of a substantial amount of discordant voxels, accounting for 31% among CALC-positive and 66% of CALC-negative voxels in CALC vs. CTRL (Fig. 3C). We also validated the presence of discordant voxels in comparison to REST (Fig. S3) and for the MEM condition (Fig. S4).

One could argue that voxels with discordant ΔBOLD simply emerge from misalignment and partial volume effects when integrating voxel data from different modalities. Thus, we conducted a replication study with matching voxel sizes and matrices across BOLD- and mqBOLD sequences and with higher voxel resolution in pCASL imaging. Using the identical analysis pipeline of the main study, we found an *n*-ratio > 1 for concordant voxels (BOLDpos/neg: 1.7/1.2) and, most crucially, a substantial amount of discordant voxels (BOLDpos/neg: 40%/40%) (Fig. S6). One could also argue about sensitivity issues of mqBOLD across cortical voxels. For example, weak ΔCBF due to low pCASL sensitivity or dominance of vascular effects (high R2' or CBV) might artificially induce discordant ΔBOLD. We, therefore, validated our results using control masks of significant ΔCBF, significant ΔCMRO2, and excluding voxels with high vascular contribution (Fig. S7). All control analyses confirmed the presence of discordant voxels for both positive (range of all control analyses: 11-29%) and negative (68-78%) ΔBOLD. Moreover, the Davis model relies on several parameters related to hemodynamics and MR-susceptibility (α, β), which influence the model's outcome (see Methods section). Yet, the original paper's sensitivity analyses indicate that their impact on the overall results of the model is "small, on the order of our standard error of measurement for a single subject" (Davis et al., 1998, page 1835).

As a final control against voxel-specific artifacts, we investigated the hemodynamic and metabolic response for both signs of ΔBOLD occurring within the same voxels (Fig. 4A, conjunction mask). We analyzed the response patterns in each of around 4.000 voxels and categorized them according to their response type. The 'concordant only' voxels displayed a canonical hemodynamic response for both positive and negative ΔBOLD, indicating that the mqBOLD method effectively detects a canonical hemodynamic response across the entire

range of ΔBOLD. The largest group, termed 'mixed' voxels, exhibited a canonical hemodynamic response for positive ΔBOLD (Fig. 4B, red) but did not show a significant CBF response for negative ΔBOLD (Fig. 4B, orange). Paradoxically, based on BOLD fMRI data alone, one would interpret activity as increased in one condition and decreased in the other, despite those voxels showing a significant increase in ΔCMRO2 of similar amplitude in both tasks (Fig. 4B red/orange bar plots).

In summary, mqBOLD is a valid approach to detect canonical hemodynamic responses. Yet, we found a substantial number of voxels with discordant ΔBOLD across different tasks and compared them to different baseline conditions. Discordant voxels occur for both positive and negative ΔBOLD, arguing against a sensitivity issue of the mqBOLD approach to detect negative hemodynamics. Moreover, we observed concordant and discordant responses within the same voxels, which argues against voxel-specific issues such as vascularization or partial volume effects. Together, this suggests that different hemodynamic mechanisms serve an increased demand for oxygen, as discussed previously. Shaw et al. reported microvascular differences in the rodent hippocampus, which may explain different neurovascular coupling in cortical and subcortical regions (Shaw et al., 2021). In humans, Devi et al. (2022) and Mullinger et al. (2014) both found discrepancies in the coupling of CBF and BOLD signal changes in sensory cortices, which they interpreted as different neurovascular coupling mechanisms, especially for negative ΔBOLD.

Baseline OEF indicates baseline metabolism and a second type of hemodynamic response during task conditions

According to Fick's principle, a ΔCMRO2 without the contribution of ΔCBF emerges from ΔOEF. We thus hypothesized different baseline OEF across voxels of varying hemodynamic response types, indicative of different oxygen buffers. Confirming this hypothesis, we found significantly different baseline OEFs across the three response types of the 'conjunction voxels' (Fig. 4C). Specifically, baseline OEF was lowest for 'discordant only' voxels and highest for 'concordant only' voxels, with 'mixed' voxels in-between. We then examined baseline hemodynamics across the entire cortex and separately for concordant and discordant voxels across all tasks of our study, which account for 32% and 21% of all GM voxels, respectively (Fig. 5A). Across the range of baseline CMRO2 of all group of voxels, we found a significant positive linear relationship with CBF and OEF (Fig. 5A, scatter plots). Further, multiple linear regression analyses indicated that the majority of CMRO2 variability is explained by OEF (>68%), followed by CBF (>28%) and CBV (>1%). Replicating the result from the subset of 'conjunction voxels', we observed a significantly lower CBF and OEF in discordant compared to concordant voxels (Fig. 5B). We also confirmed the differences in baseline OEF and CBV using separate data from quantitative susceptibility mapping (Huck et al., 2019; Lüsebrink et al., 2021) (Fig. 5C). Together, this suggests that OEF is the most prominent modulator of baseline metabolism across the human cortex, and potentially indicative of the type of hemodynamic response during task conditions.

Finally, we specifically tested whether OEF not only regulates baseline metabolism but also oxygen demand during task processing (Fig. 5D). Similar to the results during baseline, a multiple linear regression analysis revealed that ΔOEF is the major contributor (58% of the total explained variance) to regulating task-related oxygen consumption across discordant voxels. On the other hand, concordant voxels predominantly regulate ΔCMRO2 via ΔCBF (87%), confirming the canonical hemodynamic response in these voxels. This suggests that OEF is the most predictive factor for baseline metabolism across the cortex and implies that ΔOEF is a major contributor to changing oxygen demands in a significant group of voxels across the human cortex. Our findings are consistent with rodent data, which have shown different patterns of neurovascular coupling based on variations in vascular composition (Ances et al., 2008; Boorman et al., 2010; A. Ekstrom, 2010; Shaw et al., 2021).

Systematic limitations of mqBOLD and control analyses

Although the mqBOLD approach is more available and less invasive than PET, it does have several limitations. It is important to note that any systematic biases in the quantification of CBF, OEF, and CMRO2 would only impact across-subject comparisons but cannot explain task effects, as those are calculated as ΔOEF or ΔCMRO2 within the same voxels.

Absolute CBV quantification using DSC MRI is hardly possible, and it reflects total rather than venous CBV. Yet, the limitation of measuring total CBV applies to nearly all other CBV measurements in humans, such as PET (Enmi et al., 2004). To make CBV values comparable across subjects, we employed a global normalization procedure (Hirsch et al., 2014). Additionally, we followed the recommendations of our institution's Ethical Board, restricting the application of the contrast agent for DSC measurements to a maximum of one clinical dose per healthy participant. As a result, we acquired CBV during CTRL in all subjects and ΔCBV in a subset of subjects using two half-dose applications during CALC and CTRL, which has been shown to yield reliable results (Hedderich et al., 2019). Despite these limitations, our CBV data are valuable as we are unaware of any other study attempting to quantify CBV and ΔCBV during task processing in healthy subjects.

We also studied the sensitivity of our mqBOLD approach to reliably detect positive and negative ΔCBF. We replicated the amplitude and extent of decreased CBF of an earlier PET study (Fig. S2B) using a comparable analysis approach (Shulman, Corbetta, et al., 1997, S. 19). Moreover, our data demonstrate ΔCBF within regions of significant ΔBOLD, consistent with previous studies of MR-based CBF measurements (Jog et al., 2016; J. Kim et al., 2006; Qihong Zou et al., 2011).

Furthermore, CMRO2 values from white matter (WM) cannot be interpreted since T2 and T2* quantification are strongly influenced by orientation effects of myelinated nerve fibers within WM and differences in lipid concentration between GM and WM. Moreover, T2* values may be biased by magnetic background field gradients, particularly in frontobasal and temporal brain areas. In previous work, our group has carefully investigated these sources of systematic errors in OEF, particularly regarding the influence of background magnetic fields (Hirsch et al.,

2014; Hirsch & Preibisch, 2013), T2-related bias (Kaczmarz, Hyder, et al., 2020), and orientation-related effects in WM structures and error propagation (Kaczmarz, Göttler, et al., 2020). Based on these studies, we are confident that mqBOLD fMRI allows for proper investigation of GM OEF and CMRO2. Additionally, we applied proper masking to reduce partial volume effects of adjacent WM structures. Furthermore, we have recently demonstrated that mqBOLD-based OEF in GM agreed reasonably well with PET-based OEF (Kufer et al., 2022).

We also performed several control analyses to verify the study design. In the main study (Fig. 1), block durations varied for BOLD (30 sec) and quantitative (approx. 6 min) fMRI to achieve the best SNR for each modality. In a separate control study, we investigated the BOLD signal's stability across three minutes of task performance (Fig. S2E). For both positive and negative ΔBOLD, we identified stable levels of the BOLD signal across the entire period of continuous task performance of CALC and MEM. Similarly, we found sustained levels of the CBF signal across 6 min of task performance (Fig. S2E). Importantly, neither signal showed signs of habituation or drift effects across several minutes of acquisition.

Implications for the interpretation of BOLD fMRI and outlook

The discordant response type challenges the interpretation of the BOLD signal in relation to changes in neuronal activity and metabolism. In particular, negative ΔBOLD in areas with low baseline OEF may indicate increased neuronal activity and vice versa. As a solution, we recommend interpreting ΔBOLD in terms of neuronal activity only if CMRO2, or at least CBF data, are available for the same voxel and condition. In general, we propose quantitative BOLD fMRI as a more precise tool to identify regional changes in neuronal activity across the cortex. Moreover, mqBOLD methods might elucidate differences in hemodynamic status or dynamics across cohorts with known differences in vasculature, such as in healthy aging or patients with stroke or AD.

Our study offers new insights into the regional distribution of hemodynamic changes and suggests varying mechanisms across the human cortex. Firstly, voxels regulating mainly through ΔOEF appear to have a greater oxygen buffer, meaning the oxygen pressure remains sufficiently high during task engagement (Leithner et al., 2010; Leithner & Royl, 2014). Secondly, the OEF-based regulation may be linked to different signaling mechanisms, such as astrocytic activity (Takata et al., 2018), shifts in excitatory/inhibitory signaling (Buxton et al., 2014; Uhlirova et al., 2016), or neuromodulatory regulation (Koush et al., 2021). Thirdly, our findings support the necessity of quantitative mqBOLD fMRI for future research. Quantitative BOLD is particularly valuable for studying subject groups with potentially altered hemodynamics, such as during aging (Tsvetanov et al., 2020) or in neurodegenerative disorders (Chen et al., 2022), as changes in hemodynamics can significantly impact the interpretation of the BOLD signal (Archila-Melendez, M., 2020).

METHODS

Participants

Main study: We acquired data from 47 healthy human subjects, seven of whom had to be excluded because of a) apparent behavioral task difficulties (n=1), b) problems with contrast-agent application (n=2), or c) data quality problems (n=4) such as severe motion artifacts in CBF or R2' data, unilateral CBF data, or susceptibility artifacts, leaving us with a cohort of 40 healthy subjects (22 women, 18 men; mean age 32.1 ± 9.2y, all right-handed) for further analyses. While 30 of these subjects participated in all four conditions (CALC, MEM, CTRL, REST; design below), 10 subjects only performed CALC and CTRL conditions but additionally received two DSC scans during CALC and CTRL, which allows for a within-subject calculation of ΔCBV. This means that any analysis of MEM or REST only includes 30 datasets.

Control study: To investigate the stability of BOLD fMRI during extended periods of task performance, we performed BOLD fMRI of an independent cohort with 18 healthy subjects (control sample: 11 women, 7 men; mean age 28.1 ± 5.0y, all right-handed).

Replication study: To replicate the main study with identical analysis pipelines but with imaging data of matching voxel matrices and resolution across BOLD- and mqBOLD sequences, we acquired additional data from 10 healthy subjects (5 women, 5 men; mean age 31.8y ± 6.8y) performing CALC, CTRL, and MEM.

Task design

Participants were lying in the scanner in a supine position and watched the task instructions on a screen positioned behind the scanner via a mirror mounted to the head coil. Right-hand responses were collected via a button box (fORP 932, 4 Buttons, Cambridge Research Systems). Before entering the scanner, we explained all task conditions to the participants, emphasizing staying concentrated and giving correct responses rather than being fast. Before entering the scanner, participants performed a short test run of each condition on a computer outside the scanning room. All tasks were programmed to continuously engage subjects throughout the functional imaging runs of BOLD and mqBOLD fMRI.

CALC (calculation task): The CALC condition was designed to evoke negative BOLD responses in the DMN and positive BOLD responses in a task-positive network, including frontoparietal and dorsal attention networks (DAN). During CALC, participants continuously solved arithmetic tasks in a self-paced manner with a maximum response time of 10 seconds per task, similar to the design by Lin and colleagues (Lin et al., 2011b). Specifically, a row of three numbers plus a question mark (n1, n2, n3, ?) was presented with the instruction to solve the arithmetic and fill in the missing number for ? using the button box (see Fig. 1A). The solution was based on the following rule: n2 - n1 = DIFF, n2 = n1+(1*DIFF), n3 = n2+(2*DIFF), therefore ? = n3+(3*DIFF). An exemplary row is 33 38 48 ?. Here, DIFF = 5; n2 = 38 (33 + 5), n3 = 48 (38 + 2*5) and ? = 63 (48 + 15). The participants saw three response options, including the correct answer, each assigned to a button on the response box.

MEM (autobiographical memory task): The MEM condition was based on the task design of Spreng and colleagues (DuPre et al., 2016; Spreng & Grady, 2010), where participants were asked to remember a specific event in the past given a cue picture. We aimed to match the visual input across all three tasks, thus using a cue-word instead of a cue-picture. Participants were asked to recall as many details of any past event that came to their minds. The cue-word

was shown for a maximum of 15 seconds. To measure the average time it took participants to recall and gauge the ease of memory retrieval, they were instructed to press the first button twice as soon as an event came to mind. If they could not recall any event or further details, they were asked to press the second and third buttons in succession to prompt a new cue word. We utilized this double-button pressing instruction to ensure consistency in the total number of button presses across all tasks.

CTRL (low-level baseline): The CTRL condition involved a task with low-level cognitive and attentional demands. A row of random letters was displayed for a set time between 5.9 and 8.9 seconds. The participants had to press a button to indicate whether the first letter was a vowel. We used CTRL as an active baseline, ensuring that the visual input and button presses were similar to those in the CALC and MEM tasks. While studies investigating DMN activations usually used a matched control task to calculate task contrasts (Addis et al., 2007; Burianova et al., 2010; Burianova & Grady, 2007b), studies investigating DMN deactivations (i.e., negative BOLD responses) typically compare them to an uncontrolled resting state baseline (Lin et al., 2011b; Pfefferbaum et al., 2011; Raichle et al., 2001).

REST (resting state baseline): To replicate those two types of DMN contrasts, we also acquired REST data where a white fixation cross was presented on a black screen, and participants were instructed to fixate the cross throughout scanning.

MRI acquisition parameters

MRI of the main study was performed on an Elition upgrade of a 3T Philips Ingenia MR scanner (Philips Healthcare, Best, The Netherlands). The control study was conducted on a different 3T Philips Ingenia MR scanner, both using a 32-channel head coil. Multi-parametric, quantitative BOLD MRI included the following sequences:

A) Multi-echo spin-echo T2 mapping**:** 3D gradient spin echo (GRASE) readout as described previously by our group (Kaczmarz et al. 2020) with 8 echoes of even-spaced echo times (TE): TE1 = ΔTE = 16ms; TR=251; readout duration = 128ms; α=90°; voxel size 2x2x3.3mm^3; 35 slices (30 slices in 4 subjects); total acquisition time = 2:28min (for 35 slices).

B) Multi-echo gradient-echo T2* mapping, as described previously by our group (Hirsch et al., 2014; Kaczmarz, Hyder, et al., 2020): 12 echoes, TE1 = ΔTE = 5ms; TR=2229ms; readout duration = 60ms; α=30°; voxel size 2x2x3mm^3; gap 0.3mm; 35 slices (30 slices in 4 subjects). Correction for magnetic background gradients with a standard sinc-Gauss excitation pulse (Baudrexel et al., 2009; Hirsch & Preibisch, 2013); acquisition of half- and quarter-resolution data in k-space center for motion correction (Nöth et al., 2014); total acquisition time = 6:08min (for 35 slices).

C) Pseudo-continuous arterial spin labeling (pCASL): following Alsop et al. (2015) and as implemented by our group (Göttler et al., 2019; Kaczmarz, Hyder, et al., 2020). Post-labeling delay 1800ms, label duration 1800ms; 4 background suppression pulses; 2D EPI readout; TE=11ms; TR=4500ms; α=90°; 20 slices (16 slices in one subject); EPI factor 29; acquisition voxel size 3.28x3.5x6.0mm^3; gap 0.6mm; 39 dynamics plus one proton density-weighted M0 scan; total acquisition time = 6:00min.

D) Dynamic susceptibility imaging (DSC), as described previously by our group (Hedderich et al., 2019): Single-shot GRE-EPI; EPI factor 49; 80 dynamics; TR = 2.0s; α=60°; acquisition voxel size 2x2x3.5mm^3; 35 slices (30 slices in 4 subjects). Injection of gadolinium-based contrast agent as a bolus after 5 dynamics, 0.1ml/kg, minimum 6ml, maximum 8ml per

injection, flow rate: 4ml/s, additionally flushing with 25ml NaCl; total acquisition time = 2:49min (for 35 slices).

Additionally to mqBOLD sequences, we acquired

F) BOLD-fMRI using single-shot EPI, EPI factor 43; voxel size = 3.0x3.0x3.0mm^3; FOV 192x192x127.8mm^3; TE=30ms; TR=1.2s; α=70°; 40 slices; SENSE-factor = 2; MB-SENSE-factor = 2. For susceptibility correction, a B0 field map was acquired with two echoes; TR/TE1/TE2=525ms/6.0ms/9.8ms; 40 slices; parallel acquisition; α=60°; voxel size = 3.0x3.0.3.0mm^3; FOV 192x192x127.8mm^3; total acquisition time: 0:35s.

G) T1-weighted 3D MPRAGE pre- and post-gadolinium (TI/TR/TE/α = 100ms/9ms/4ms/8°; CS-SENSE-factor=7.5; 170 slices; FOV=240x252x170 mm^3; voxel size 1.0x1.0x1.0mm^3; acquisition time=2:05min) and T2-weighted 3D FLAIR (fluid-attenuated inversion recovery; TR/TE/α = 4800/293/40°; CS-SENSE-factor=10; 140 slices; FOV=240x248.9x168mm^3; acquisition voxel size 1.2x1.2x1.2mm^3; turbo spin-echo factor 170; inversion delay 1650ms; acquisition time=2:09min) images were acquired for anatomical reference and to exclude brain lesions.

Imaging for the control study included T1-weighted 3D MPRAGE and BOLD-fMRI, all acquisition parameters identical to those described above.

The imaging parameters for the replication study with matching voxel matrices were:

T1-weighted 3D MPRAGE, multi-echo spin-echo T2 mapping and multi-echo gradient-echo T2* mapping as described above (T2/T2* voxel size = 2x2x3.3mm^3). BOLD-fMRI was acquired as described above, yet with a voxel acquisition size = 4x4x3mm^3, gap 0.3mm, 40 slices. PCASL was acquired as described above, yet with the same voxel size as BOLD fMRI (4x4x3mm^3, gap 0.3mm; 26 slices). This results in subject data acquired with harmonized voxel dimensions of identical BOLD/pCASL voxel sizes and four T2/T2* voxels per BOLD voxel in the x/y-plane. Please note that whole-brain coverage was not possible with this higher-resolution pCASL sequence. We, therefore, placed the volume with identical angulation to the other sequences and covered all main regions of interest from our main study (see 'brain coverage,' Fig. S6).

Data acquisition

After giving informed written consent, a medical doctor placed a venous catheter into the forearm, and blood samples were taken to measure hemoglobin, hematocrit (Hct), and creatinine values. Contrast agent before DSC measurements was only applied if creatinine values were normal to ensure healthy kidney function. Arterial oxygen saturation was measured via a pulse oximeter (Nonin 7500FO, Nonin Medical B.V., The Netherlands).

Main study: Please find an illustration of the imaging session of the main study in Fig. 1B.

BOLD fMRI: All four task conditions were presented using a 30s-block-design with four repetitions per condition, the four conditions randomized within each repetition block (400 dynamic scans plus two dummy scans, total acquisition time: 8:05min). We also acquired continuous resting-state BOLD fMRI data (500 dynamics, total acquisition time: 10:05min) that have not been used so far.

Across subjects, the entire BOLD-fMRI run was alternated with the mqBOLD fMRI runs to balance potential habituation or fatigue effects. During mqBOLD imaging, conditions were presented in pseudo-randomized order for pCASL and T2* mapping. One T2 mapping (CTRL)

was also included to account for stable tissue properties during mqBOLD calculation. DSC (CTRL) and T1w post-gadolinium scans were performed at the end of the imaging session to avoid signal artifacts from the contrast agent in any other sequence. The contrast agent was administered through a venous catheter via a dedicated pump (Accutron MR, Medtron AG, Saarbrücken, Germany) in the presence of a medical doctor.

To gain insight into their performance during the MEM condition, participants were asked to complete a memory questionnaire after the imaging session. They had to indicate how easy they found it to recall concrete events of the MEM task on a difficulty scale (1='very easy', 2='rather easy', 3='rather difficult', 4='very difficult') and how detailed their memories were overall on a concreteness scale (1='very detailed', 2='rather detailed', 3='rather vague', 4='very vague'). On average, people scored 1.8 +/- 0.7 on the difficulty scale and 2.0 +/- 0.6 on the concreteness scale. This indicates that, on average, it was relatively easy for the subjects to recall a concrete event, and the memories were rather detailed. This was consistent with the reaction times, as it took participants, on average, only 2.5 ± 1s to recall an event.

A subsample of N=10 subjects from the main study performed only the CALC and CTRL conditions but additionally received two DSC scans (two half-doses of contrast agent, totaling a full clinical dose of maximally 16ml). This allowed us to calculate within-subject ΔCBV of task effects in this subsample.

Control study: Here, we only acquired fMRI BOLD data during extended task blocks of CALC and MEM (3 min each), interleaved with 1min CTRL blocks, each task repeated four times. This resulted in a total scan time of 33 minutes.

Replication study: This study aimed to replicate the results of the main study with matching voxel matrices and resolution across sequences. We acquired structural T1w, T2, and T2* mapping as described above. BOLD fMRI and pCASL data were acquired with identical voxel resolution. BOLD fMRI task data were again acquired during all four conditions, CBF data during CALC and CTRL. For the CBV data, we used the main study's group-median maps for CALC and CTRL.

Image processing

Processing of BOLD fMRI data

BOLD fMRI data were pre-processed running fMRIPrep 20.2.4 (Esteban, 2019) in a docker container based on Nipype 1.6.1 (Gorgolewski et al., 2011). This includes the following preprocessing steps: segmentation, estimation of motion parameters and other confounds, correction for susceptibility distortions, co-registration in native T1w space, and normalization to MNI152-ICBM-2mm space with a non-linear 6th generation registration model developed by (Montreal Neurological Institute, McGill University). fMRIPrep relies on FSL 5.0.9 (Jenkinson et al., 2012; Smith et al., 2004) to register EPI time-series data to T1w data with boundary-based registration (BBR), FSL FAST for brain tissue segmentation, and ANTs 2.3.3 (Avants et al., 2008) for spatial normalization to MNI space in a multiscale, mutual-information based, nonlinear registration scheme, where all transforms are first concatenated and registration steps applied at once.

Calculation of quantitative parameter maps from mqBOLD data

We calculated all quantitative parameter maps using in-house scripts (in Matlab) and SPM12 (Wellcome Trust Centre for Neuroimaging, UCL, London, UK). Fig.1 illustrates the procedure and shows subject-averaged parameter maps, calculated as subject median across total GM. Tissue masks and artifact areas were defined and calculated in native space (see below) separately for each condition.

T2/T2*-mapping: Quantitative T2 and T2* parameter maps are obtained by applying mono-exponential fits to the multi-echo spin and gradient echo data, as described previously by our group (Hirsch et al., 2014; Kaczmarz, Hyder, et al., 2020; Preibisch et al., 2008). Corrections for macroscopic magnetic background fields (Hirsch & Preibisch, 2013) and motion were applied, the latter by redundant acquisitions of k-space centers (Nöth et al., 2014).

R2' maps are calculated via

$$R2' = \frac{1}{T2*} - \frac{1}{T2} \qquad [1]$$

yielding the transverse, reversible relaxation rate that depends on the vascular dHb content in a voxel (Blockley et al., 2013, 2015; Bright et al., 2019). Caution needs to be applied when interpreting these values at air-tissue boundaries (magnetic field inhomogeneities) or in deep GM (iron deposition) or WM structures (orientation effects in myelin), as discussed previously (Hirsch & Preibisch, 2013; Kaczmarz, Hyder, et al., 2020).

CBV is derived from DSC MRI after contrast agent application via full integration of leakage-corrected ΔR2*-curves (Boxermann, J.L., Schmainda, K.M., Weisskoff, R.M., 2006) and subsequent normalization to a white matter value of 2.5% (Leenders et al., 1990). The DSC procedure has been described previously by our group (Hedderich et al., 2019; Kluge et al., 2016).

OEF is calculated from R2' and CBV parameter maps via the mqBOLD approach (Christen et al., 2012; Yablonskiy & Haacke, 1994) and, as previously implemented by our group (Hirsch et al., 2014) via

$$OEF = \frac{R2'}{c \cdot CBV} \qquad [2]$$

with $c = \gamma \cdot \frac{4}{3} \cdot \pi \cdot \Delta\chi_0 \cdot hct \cdot B_0$, and specific parameters for the gyromagnetic ratio $\gamma = 2.675 \cdot 10^8\ s^{-1}\ T^{-1}$, the susceptibility difference between fully deoxygenated and oxygenated hemoglobin of $\Delta\chi_0 = 0.264 \cdot 10^{-6}$, the magnetic field strength $B_0 = 3T$ and the small-vessel hematocrit *hct*, which is calculated as 85% of the empirically measured (large-vessel) hematocrit values of each subject (Eichling et al., 1975; Hirsch et al., 2014).

CBF maps were calculated from pCASL data as described in (Alsop et al., 2015). Specifically, CBF is calculated as the pairwise differences of the averaged and motion-corrected label and control images and scaled by a proton-density weighted image.

CMRO2: For each condition separately, we then calculated the voxel-wise CMRO2 by combining all parameter maps via Fick's principle:

$$CMRO2 = OEF \cdot CBF \cdot C_aO_2 \qquad [3]$$

where C_aO_2 is the oxygen-carrying capacity of hemoglobin and was calculated as $C_aO_2 = 0.334 \cdot Hct \cdot 55.6 \cdot O_2sat$, with O_2sat being the oxygen saturation measured by a pulse oximeter (Bright et al., 2019; Ma et al., 2020). CBF values were upscaled by 25% to account for the systematic underestimation of CBF due to the four background suppression pulses, as motivated here (Garcia et al., 2005; Mutsaerts et al., 2014).

All parameter maps were calculated in subject space and co-registered to the first echo of the T2 data. Any normalization into MNI space was performed afterward. Specifically, all mqBOLD parameter maps were first co-registered to native T1w space before applying the normalization matrix to MNI space, as derived from fMRIPrep.

Artifact correction and GM masking

To exclude voxels from artifact-affected brain areas, we calculated the temporal signal-to-noise ratio (tSNR) from the BOLD fMRI data per subject and voxel and transformed individual masks into MNI space. We then created a conjunction mask on the group level, excluding voxels from the lowest 15th percentile of tSNR in over 66% of participants. These were mainly located in areas with strong susceptibility perturbations, i.e., fronto- and temporo-basal brain areas. Additionally, we masked out the cerebellum and voxels with a GM probability < 0.5. The resulting group mask was applied to the output of the GLM group analysis and the input matrices for the partial least squares analyses. For the analyses in native space, we additionally used native-space parameter maps to mask CSF-prone areas (T2 > 90ms), high-susceptibility areas (R2' > 9 s^{-1}), voxels with a high percentage of blood volume (CBV >10%, probably driven by larger veins/arteries) and voxels with biologically implausible values, such as T2' > 90ms, OEF > 0.9, and CBF > 90ml/100g/min.

Estimation of a realistic surrogate for CBV during CALC

During the evaluation of our study by the Ethics Board of the University Hospital, we agreed on using one typical clinical dosage of contrast agent as the maximum to measure CBV in healthy subjects. We, therefore, acquired DSC data during CTRL as a baseline measurement of CBV across the individual cortex. However, following a sensitivity analysis of another dataset at our institution, we learned that half the clinical dosage was enough to reliably evaluate CBV in healthy subjects. To our knowledge, there is no empirical data on ΔCBV for cognitive task processing in humans. As a result, we collected two separate DSC datasets for the final subset of 10 subjects, each receiving two half dosages during CALC and CTRL.

From these measurements, we determined the voxel ΔCBV for CALC compared to CTRL in subject space and averaged it within 360 functional regions of interest (ROIs) as defined by (Glasser, 2016). We then calculated the median change per ROI across the 10 subjects to estimate ΔCBV for a template brain. Using this average ΔCBV map, we estimated a realistic CBV surrogate map during CALC for the remaining 30 subjects, for whom only one baseline CBV measurement was available. We used the CBV CTRL map to calculate the MEM condition, as no CBV measurements were available during MEM. To our knowledge, this is the most empirically based data used for ΔCBV in quantitative fMRI studies.

Semi-quantitative CMRO2 estimation

The fully quantitative estimation of CMRO2 maps relies on the combination of R2', CBV, and CBF values, according to Eq. [3]. To control for potential error propagation, especially from R2' measurements (see appendix in (Kaczmarz, Göttler, et al., 2020), we calculated semi-quantitative CMRO2 and OEF values from BOLD fMRI data as suggested by Fujita et al. (2006). Instead of calculating ΔR2' from quantitative R2' (multi-echo GE-based T2*) during task conditions, ΔR2' is approximated as

$$\Delta R2' = -\frac{\Delta S}{S_0}\frac{1}{TE \cdot R2'_0} \quad [4]$$

with TE = 30ms, $R2'_0$ being the baseline R2', and $\frac{\Delta S}{S_0}$ the BOLD signal change, derived from task data. R2' in CALC and MEM was calculated via $R2' = R2'_0 + (\Delta R2' \cdot R2'_0)$ and fed into OEF and CMRO2 calculations according to Eqs. [2] and [3]. Thus, semi-quantitative CMRO2 values, inferred from BOLD fMRI signal changes, differ from fully quantitative CMRO2 values only using task R2' values. In Fig. S5, we directly compared the results from both approaches and found very similar signal ranges and voxel distributions.

Davis model

The original Davis model was originally used for calibrated fMRI and is a simulation of ΔBOLD (= $\Delta S/S_0$) using carbon dioxide breathing as a physiological means of manipulating CBF independent of CMRO2 and relying on M, α, and β (Davis et al., 1998):

$$\frac{\Delta S}{S_0} = M\left[1 - \left(\frac{CBF}{CBF_0}\right)^{\alpha-\beta}\left(\frac{CMRO2}{CMRO2_0}\right)^{\beta}\right] \quad [5]$$

where α is a power-law exponent, relating CBV to CBF changes, and β depends on the microvascular anatomy (Bright et al., 2019). Previously, α = 0.38 was used, (Grubb et al., 1974) but much lower values have recently been identified. We used the parameters derived from invasive rodent imaging and simulations (Gagnon et al., 2016) with α = -0.05 and β = 0.98, as proposed for human measurements on a 3T scanner with TE = 30ms. M is commonly referred to as the maximum ΔBOLD that occurs if all dHb is washed out of the vessels; it depends on baseline OEF (Blockley et al., 2013). For the calibration of fMRI experiments, M is estimated via combined measurement of CBF and BOLD responses to a vasoactive stimulus, mostly hypercapnia. Assuming α and β, the fractional change in CMRO2 can be calculated from combined BOLD signal and CBF measurements during tasks (Blockley et al., 2013; Chen et al., 2022; Germuska & Wise, 2019). Importantly, we did not use the Davis model to estimate our results; instead, we used it to independently model a range of realistic CBF, CMRO2, and BOLD changes and compare those to our empirical data and CMRO2 as calculated above.

Statistics

Partial least squares analysis of BOLD and mqBOLD data

Partial least squares (PLS) analyses were performed using the pyls library in Python language (Python Software Foundation, version 3.8). Mean-centered PLS is a data-reduction method that computes latent variables and corresponding brain patterns, which optimally relate brain signals to the experimental design, contrasting, e.g., groups or conditions (McIntosh & Lobaugh, 2004). In our case, the input-data matrix to calculate a contrast of interest contained one row for each subject, including all voxels within the artifact-corrected mask (see above), stacked across conditions of interest, e.g., CALC and CTRL. In the case of BOLD fMRI data, median values of percent signal change (from either CTRL or REST) across 24s (20 TRs) per task condition were used, excluding the first 6s per task block to account for the hemodynamic response lag. For mqBOLD data, quantitative OEF, CBF, or CMRO2 values per voxel and subject were used for all conditions. With the help of a dummy-coding matrix, the pyls library computes within-condition averages, which are column-wise mean-centered (Krishnan et al.,

2011). This matrix, $R_{mean\text{-}centered\ (q\ x\ p)}$, which comprises q conditions and p voxels, is then subjected to singular value decomposition, which results in:

$$R'_{mean\text{-}centered} = USV' \quad [5]$$

where $U_{p\,x\,q}$ are the voxel weights (brain saliences), one row per latent variable (LV), that reflect how much this voxel contributes to the effect captured by LV_i. $V_{q\ x\ q}$ is the matrix of task saliences (one row per LV) that indicates how each condition contributes to the spatial pattern identified by LV_i. $S_{q\,x\,q}$ are the singular values per LV that reflect the strength of the relationship extracted by each LV_i (McIntosh & Mišić, 2013). The significance of the LVs, i.e., the entire multivariate pattern, was tested via permutation tests (3000 permutations), and the reliability of the brain saliences, i.e., the voxel's contribution to the LVs, was deduced via bootstrap resampling (3000 samples). Brain regions showing significant effects were identified via the ratio of the brain saliences to the bootstrap standard error (BSR), where a BSR > ±2 is akin to a confidence interval of 95% if the bootstrap distribution is normal (Krishnan et al., 2011; McIntosh & Mišić, 2013). In this paper, we used PLS analyses to perform group-level statistics to identify brain regions that best differentiate between a task (CALC or MEM) and a baseline (CTRL or REST) condition. As the same analysis was applied to both BOLD fMRI and mqBOLD data, resulting statistical maps can be compared across the different parameters. The statistical maps were thresholded with a BSR of ±2, and only clusters with more than 30 voxels were kept for creating group masks. For correct interpretation, BSR maps must be compared to the design scores (design variables multiplied by brain saliences) of each condition within each LV to know the direction of task differences captured by the BSR pattern. In this manuscript, an orange-red BSR pattern indicates a positive task effect, that is, voxels with higher values during the task compared to the baseline, whereas blue voxels show the opposite contrast.

BOLD clusters

The BOLD clusters shown in Fig. 2D are based on the PLS analysis of the BOLD data. Statistical maps were thresholded with a BSR > +/-3. Connected regions with a minimum region size of 1000 voxels were extracted using Nilearn's region package in Python. Then, upon visual inspection, clusters that apparently were fractionated by the algorithm but that belonged together based on Yeo's network templates (Thomas Yeo et al., 2011) were again fused.

General linear modeling of BOLD data

As a control for PLS analysis, a general linear model (GLM) approach for task analysis was implemented following recommendations (Esteban et al., 2020).

We set up a GLM with separate confound columns (CSF, WM signal, dvars, framewise displacement, translations/rotations in x-, y- and z-axis) and applied a high-pass filter of 100s and a 6mm smoothing kernel. For native-space analyses based on GLM masks, we used individual 1st-level z-maps, z > 2.5. The following contrasts were calculated: CALC-positive = CALC > CTRL or REST, CALC-negative = CALC < CTRL or REST, MEM-positive = MEM > CTRL, MEM-negative = MEM < CTRL.

CBF peak ROIs

To compare our data to CBF data generated from PET imaging, we used a similar approach described in the seminal paper by Shulman and colleagues (Shulman, FIEZ, et al., 1997). We calculated median ΔCBF[%] across subjects, with a threshold of CBF < -2% and without further corrections (Fig. S2B). CBF peak ROIs were derived from the PLS-derived statistical group map, as shown in Fig. S2B on the right. We used the atlasreader library in Python (Notter et al., 2019) to extract peak coordinates. We then selected the coordinates of nine (out of 15) peaks with the highest positive peak values, plus all seven peaks with negative peak values, to create spheres with 5mm diameter around these coordinates. Median CBF and CMRO2 responses were extracted within these spheres to compare CALC versus REST conditions and to the original figure in the Shulman et al. paper.

Other statistical analyses

For the native space analyses, we calculated median values within each native-space ROI (output of the first level GLM, thresholded with z>3.1) per subject and tested significant differences in tasks compared to baseline via separate paired-samples, two-sided, t-tests, across subjects. All other statistics were based on median voxel values within a group mask in standard space by taking the across-subjects median value per voxel in task and baseline (Fig. 2B, Fig. 3B, Fig. 4A&D). Barplots showing median voxel values were generated via Python's seaborn library (Waskom, 2021), with error bars showing a 95% confidence interval (CI) using 2000 permutations. If the CI included zero, the median delta value was defined as statistically non-significant. To test differences in hemodynamics between discordant and concordant voxels, we used paired, two-sided t-tests on the median subject values; to test for baseline differences, we used independent-sample permutation tests on the median voxel values. External, high-resolution maps were downsampled to 2mm MNI standard space before analyses were conducted.

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DATA and CODE AVAILABILITY

All raw and processed data are available in the online repository of OpenNeuro (Epp et al., 2023) (https://openneuro.org/datasets/ds004873). The scripts, Python Jupyter notebooks, docker container for quantitative parameter map analyses, and configuration files for replication of all analyses and figures are available on GitHub (https://github.com/NeuroenergeticsLab/two_modes_of_hemodynamics).

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