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What's in a pattern? Examining the type of signal multivariate analysis uncovers at the group level☆

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ABSTRACT

Multivoxel pattern analysis (MVPA) has gained enormous popularity in the neuroimaging community over the past few years. At the group level, most MVPA studies adopt an “information based” approach in which the sign of the effect of individual subjects is discarded and a non-directional summary statistic is carried over to the second level. This is in contrast to a directional “activation based” approach typical in univariate group level analysis, in which both signal magnitude and sign are taken into account. The transition from examining effects in one voxel at a time vs. several voxels (univariate vs. multivariate) has thus tacitly entailed a transition from directional to non-directional signal definition at the group level. While a directional group-level MVPA approach implies that individuals have similar multivariate spatial patterns of activity, in a non-directional approach each individual may have a distinct spatial pattern. Using an experimental dataset, we show that directional and non-directional group-level MVPA approaches uncover distinct brain regions with only partial overlap. We propose a method to quantify the degree of spatial similarity in activation patterns over subjects. Applied to an auditory task, we find higher values in auditory regions compared to control regions.

Introduction

In the last decade, the use of multivoxel pattern analysis (MVPA) to analyze fMRI data has grown substantially and is now commonplace (Haxby, 2012; Haynes and Rees, 2006; Kriegeskorte et al., 2006a; Poldrack and Farah, 2015; Tong and Pratte, 2012). The increasing use of MVPA approaches compared to classical univariate approaches has also tacitly implied a move from a directional to a non-directional definition of signal at the group level. Here we expose this shift in the definition of signal, impacting popular MVPA approaches in group inference. In addition, we suggest a novel application of recently developed statistical measures to address this issue. Our proposed statistic has the added benefit of quantifying the degree to which subjects share multivariate patterns of activity at the group level.

We focus on examples in which the signal of two conditions is compared. In a typical mass-univariate analysis, the BOLD signal in each individual voxel is examined separately by comparing values between conditions at the individual subject level (first level). This is typically conducted by performing a *t*-test examining the null hypothesis that the expected response is not different across conditions. In multivariate approaches, a spatial pattern of activity is compared (Haxby et al., 2001). Commonly in such cases, supervised machine learning approaches such as linear discriminant analysis or support vector machines (Kragel et al., 2012; Misaki et al., 2010; Mur et al., 2009; Tong and Pratte, 2012) are used, and their results are compared against an empirical null distribution - putatively centered around chance classification levels.

At the second (group) level, univariate studies use a random effects (RFX) analysis to examine whether the average difference between two conditions is consistent across subjects. If the mean difference between conditions is significantly different from zero (as examined using a *t*-test for example), the voxel is declared responsive at the group level. Since the difference between conditions is signed, to reject the null one must show a *directional* group-wise effect (Fig. 1A). A directional effect is one in which most subjects display a consistent (either positive or negative) effect in a given voxel. This takes into account both

☆ We offer code at https://github.com/roeegilron/MVPAtesting/ and maps at http://neurovault.org/collections/978/, Original data can be found at https://openfmri.org/dataset/ds000158.

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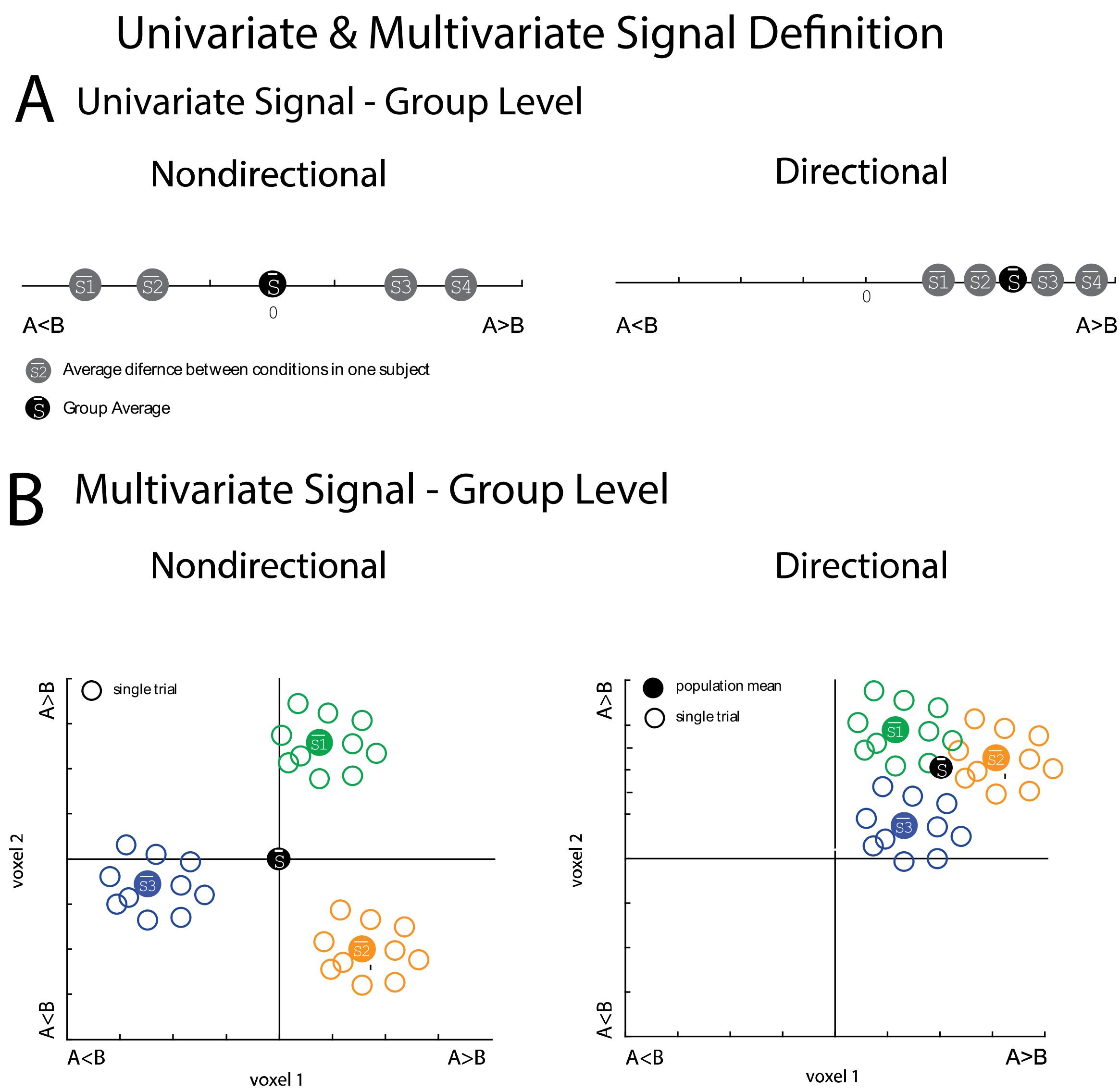

Fig. 1. Univariate and multivariate signal definition. This schematic diagram represents the different signal definitions in univariate and multivariate approaches employing either a directional or non-directional analysis. (A) Univariate group level analysis. Grey colored circles represent the average difference (contrast) between conditions of interest (A and B) of individual subjects. The group average is represented by a filled black circle. In a directional univariate analysis, activation is defined as a group average that is different from zero (conceptual example - top right). In contrast, in a non-directional univariate analysis the voxel may be declared active even if the mean of the contrast across subjects is zero (top left). (B) Multivariate group level analysis. Empty circles represent single trials, filled circles represent average difference of single subject, and black filled circle is group average. In a non-directional multivariate analysis a beam is considered active provided that subjects are not all at zero (left). Note that the group average can be centered at zero. In contrast, in a directional multivariate analysis subjects share a spatial pattern of activity such that the beam is considered active if the group average is away from zero (conceptual example - right). The non-directional approach is the most commonly used in the 2nd level multivariate analysis, whereas the directional approach is the most commonly used in 2nd level univariate analysis.

magnitude and sign (direction) of the effect. This directional effect has been termed “activation based” to emphasize its origin. If, for example, we had a cohort of subjects in which half of the sample showed an *increase* in their response to one condition relative to the other while the other half showed a *decrease* of equal magnitude in their response – a second level directional analysis would not define such a group effect as signal. A *directional* group wise effect implies that subjects share a similar spatial pattern of activity, henceforth referred to as *similarity*. Put differently, variability in pattern similarity is part of the RFX null hypothesis and not part of the alternative. Although there is a strong effect size at the individual subject level, at the group level there is no significant effect under such a directional definition of signal. Indeed, a *directional* approach is the commonly adopted signal definition in second-level mass-univariate RFX analysis.

In contrast, the large majority of MVPA studies to date have adopted a *non-directional* (information based) definition of signal at the group level (Fig. 1B). In a *non-directional* analysis, a certain statistic (usually classification accuracy) is calculated at the individual subject level, and this statistic is then carried over to the second level. Note that as opposed to the t-statistic (or beta contrast), the accuracy statistic is directionless, thus the sign of the effect at the first level is lost and only its magnitude is passed on to the second level. In the example described earlier (see also Fig. 1A – left) half of the subjects show an increase in their response to condition 1 vs. condition 2 while the other half of subjects show a decrease of equal magnitude. Thus effect size at the individual subject level is large and would be reflected in a corresponding high statistical value (e.g. classification accuracy) that is carried to the second level. Since all subjects have a large effect size, such a case would be detected by a non-directional 2nd level analysis, irrespective of the fact that different subjects show completely opposite patterns of responses. The equivalent univariate null hypothesis of a *non-directional* signal definition is that across subjects, the