Combining stimulus types for improved coverage in population receptive field mapping

David Linhardt a, Maximilian Pawloff b, Allan Hummer a, Michael Woletz a, Martin Tik a, Markus Ritter b, Ursula Schmidt-Erfurth b, Christian Windischberger a,⁎

a High Field MR Center, Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, Vienna, Austria
b Department of Ophthalmology, Medical University of Vienna, Vienna, Austria

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A B S T R A C T

Retinotopy experiments using population receptive field (pRF) mapping are ideal for assigning regions in the visual field to cortical brain areas. While various designs for visual stimulation were suggested in the literature, all have specific shortcomings regarding visual field coverage. Here we acquired high-resolution 7 Tesla fMRI data to compare pRF-based coverage maps obtained with the two most commonly used stimulus variants: moving bars; rotating wedges and expanding rings. We find that stimulus selection biases the spatial distribution of pRF centres. In addition, eccentricity values and pRF sizes obtained from wedge/ring or bar stimulation runs show systematic differences. Wedge/ring stimulation results show lower eccentricity values and strongly reduced pRF sizes compared to bar stimulation runs. Statistical comparison shows significantly higher pRF centre numbers in the foveal 2° region of the visual field for wedge/ring compared to bar stimuli. We suggest and evaluate approaches for combining pRF data from different visual field patterns to obtain improved mapping results.

1. Introduction

Retinotopy refers to the preservation of retinal adjacency via the visual stream to the primary visual cortex. It is one of the most remarkable features in human visual neuroanatomy. Among the first reports on topographical (retinotopic) maps were lesion studies in soldiers that showed correlations between visual field loss patterns and visual cortex damages (Henschen, 1893; Holmes, 1918; Inouye, 1909).

Functional magnetic resonance imaging (fMRI) has become the prime technique for mapping human brain function and is ideally suited for studying retinotopy as shown in the seminal studies by Engel and others (Engel et al., 1994) (for a review see, e.g. Wandell and Winawer, 2011). In the classic paradigm, concentric, expanding rings are presented periodically to the participants. This causes sinusoidal activation time-courses in the visual cortex where phase encodes eccentricity within the visual field. Combined with a second set of stimuli comprising rotated wedges, these travelling-wave paradigms allow for mapping visual field positions to locations on the visual cortex (Sereno et al., 1995).

Population receptive field (pRF) mapping represents an extension to the earlier retinotopic mapping approaches. As a model-driven approach, neuronal receptive fields are estimated and allow for detailed characterization of the visual field representation on the cortical surface (Dumoulin and Wandell, 2008). Here, a receptive field (RF) describes the region of visual space that leads to neural activity in a specific cortical site. As the spatial resolution in fMRI is limited, it is not possible to estimate receptive fields of individual neurons. However, due to the retinotopic organization, neurons with similar receptive fields are located adjacently. Every voxel in the fMRI dataset, therefore, represents a population of neurons, giving the method its name. In the most straightforward case, each voxel’s pRF is estimated in the fitting process as a two-dimensional Gaussian function with the parameters position (x, y) and size (σ). Modified fitting functions such as a difference of Gaussians (Zuiderbaan et al., 2012) or elliptical Gaussians (Silson et al., 2018b) were also suggested. While the difference of Gaussians approach was reported to allow for improved fitting compared to the circular model, no such benefits were shown for elliptical Gaussians (Lerma-Usabiaga et al., 2021; Zeidman et al., 2018). In order to approximate model time courses to the actual fMRI signal changes, fitting parameters are typically optimized independently for each voxel.

As the current pRF mapping methodology is not based on phase maps, it is no longer necessary to rely on stimuli that repeatedly cover the same area on the visual field (e.g. rotating wedge and expanding ring). Even more, with the introduction of pRF mapping, arbitrary stimulus patterns may be used for assessing the retinotopic features in the visual system.
In addition to expanding rings and rotating wedges, Dumoulin and Wandell suggested a bar aperture, revealing a reversing checkerboard moving through the visual field of view in different directions (Dumoulin and Wandell, 2008). In contrast, other researchers introduced new or slightly modified stimulus variants aimed at improving accuracy compared to conventional monochrome checkerboards. One example are visual stimuli involving natural scenes (Silson et al., 2015; van Dijk et al., 2016) that greatly improved contrast in higher visual areas. Other approaches investigated the influence of chromatic stimuli (Welbourne et al., 2018).

An important retinotopic feature of the visual system is that pRF sizes vary with eccentricity, i.e. small, central parts of the visual field are mapped to disproportionately large cortical areas. To compensate for this cortical magnification effect, sweeping bar stimuli scaling logarithmically with eccentricity were tested (Cowey and Rolls, 1974). Further, it has been proposed to simultaneously present wedge and ring stimuli, an approach that was reported to maximize the number of signal peaks across the visual field and therefore yield improved model fitting (Alvarez et al., 2015). Similar to the combination of wedge and ring, the combination of two simultaneous bars was investigated (Miranda et al., 2018). For minimizing the spatiotemporal correlations, multifocal stimuli were introduced (Ma et al., 2013a; Vanni et al., 2005), where segments of the visual field are stimulated in pseudo-random order. While such stimuli were described as the optimal choice for retinotopic mapping (Buraças and Boynton, 2002), it opened a debate on the influence of stimulus predictability on the induced BOLD response. Ekman et al. (2017) showed that indicating only the start of visual stimulus triggered an activity wave in V1 that resembled the full stimulus sequence. Contrary, no influence of cueing the next area of stimulation on the resulting pRF fit was found.

Recent pRF studies have demonstrated that predictable stimuli result in improved goodness-of-fit, more robust fits compared to their pseudo-random counterparts (Binda et al., 2013; Infanti and Schwarzkopf, 2020). In addition, non-predictable stimuli may fail to fully stimulate large-size pRFs and are not suited for investigating visual areas higher than V1-V3 (Binda et al., 2013; Ma et al., 2013b). In addition to the issues of stimulus selection, recent studies also showed that pRF results are influenced by non-stimulus related parameters, as additional attention tasks led to a shift in pRF parameters towards the point of attention within the whole field of view (Klein et al., 2014).

Nevertheless, classic wedge and ring and sweeping bar stimuli remain the prime pRF mapping approaches today. In this study, we used ultra-high magnetic field (7T) fMRI data sets to compare pRF mapping results between these two most common retinotopic stimuli: rotating wedge and expanding/contracting ring versus moving bar. We focus on visual field coverage and assess whether the different stimulus characteristics yield benefits across the visual field. We also compare eccentricity, polar angle, and pRF size estimates between wedge and ring and bar stimulation results. Finally, we probe novel approaches for combining pRF results obtained from wedge and bar stimulation runs.

2. Methods

2.1. Subjects

Ten subjects (6 male, 4 female; age 25.0±2.8) participated in this study. Only subjects with a refractive error of less than 6 diopters and without significant ocular disease, history of trauma or eye surgery were included. They were naive to the experiment, were introduced to the stimuli only shortly before the measurement and received no further training. Subjects gave informed written consent and received financial compensation for their participation. The research project was approved by the local ethics committee.

2.2. MRI measurements

All measurements were performed on an ultra-high field 7 Tesla MAGNETOM scanner (Siemens Healthineers, Erlangen, Germany) using a 32-channel head coil. Functional data were acquired using the CMRR EPI sequence (Moeller et al., 2010) measuring 32 slices with 1 mm isotropic resolution and the following parameters: TE=25 ms, TR=1000 ms, multiband factor=2, GRAPPA acceleration=2, slice spacing=10 %. Independent of the stimulation paradigm used, 336 volumes were acquired per run, corresponding to a run time of about 5.5 minutes. Slices were positioned orthogonally to the calcarine sulcus, covering 35.2 mm of the occipital cortex. Additionally, B0 field maps were acquired for distortion correction. Anatomical imaging was performed using a magnetization-prepared rapid gradient-echo (MPRAGE) sequence with 0.7 mm isotropic resolution (TE=3.66 ms; TR=1960 ms).

Stimuli were projected on a rear-projection screen, which the subject can see through a mirror mounted inside the head-coil. To minimize reflections, the presentation screen is directly mounted on the patient table, as close to the participant as possible, resulting in a distance to the eye of about 62 cm.

2.3. Stimuli

Two different stimulus variants were used: wedge and bar. Each covered the central 14° of the subjects’ visual field. Subjects were instructed to fixate a central dot and report colour changes to ensure fixation and quantify the subjects’ attention during the task. All stimuli are shapes exposing an 8 Hz black-white reversing checkerboard. The background’s grey value is based on the mean luminescence of the reversing checkerboard, determined by photometric measurements. Independent of the stimulus type, every point on the visual field is stimulated eight times per run.

The first stimulus variant is derived from the classic wedge and ring stimulus. It starts with a counter-clockwise rotating wedge, with a width of 45° and a step size of 10°, performing two full rotations in 72 steps. The second part of the stimulus consists of a ring with a thickness of 0.875° visual angle and expands twice from the centre to the edges in 72 steps (step size 0.2°). This whole sequence is repeated with opposite directions, i.e. clockwise rotating wedge and contracting ring. Between each wedge or ring period, the grey background image was shown for twelve seconds as a baseline. The exposed checkerboard is radial-symmetric.

The second stimulus variant is based on the sweeping bar stimulus introduced by Dumoulin and Wandell (Dumoulin and Wandell, 2008). The bar starts moving from left to right, with a width of 1.75° visual angle and a step size of 0.4° visual angle for 36 steps per direction. After every crossing, the bar is rotated clockwise by 45°. One run comprises a total of eight different directions of screen crossings. The grey background image was shown for twelve seconds after each diagonal crossing as a baseline. The exposed reversing checkerboard pattern is a rectangular grid, tilted in the same direction as the stimulus is moving. Both stimuli are shown in Fig. 1. For stimulus creation and pRF analysis, the Matlab toolbox mrVista (https://web.stanford.edu/group/vista/cgi-bin/wiki/index.php/MrVista) was used. Run-length for each stimulus variant was 336s. Four runs were acquired in each subject, two for each stimulus variant. Run order was randomised across subjects.

2.4. Analysis

Preprocessing of functional data included slice-timing correction using SPM12 (https://www.fil.ion.ucl.ac.uk/spm) in Matlab 9.6 (Matlab, 2018), as well as realignment (SPM) and distortion correction using the acquired field maps and FSL FUGUE (Jenkinson, 2003). Functional data was spatially smoothed using a Gaussian kernel with 2 mm FWHM.
rotating wedge
definition
expanding ring

sweeping bar
time

Fig. 1. Representative images from the two stimuli used. The different aperture shapes uncover a reversing checkerboard and move in discrete steps every TR. Subjects were instructed to fixate the central dot and report colour changes by button-press. The top two rows show the wedge/ring stimulus. The ring is expanding from the centre to the edges and back while the wedge rotates in both directions subsequently. The bottom row shows the bar stimulus, where the bar is moving through the visual field along eight different directions rotated in steps of 45°.

For obtaining cortical grey matter masks, segmentation using the Freesurfer image analysis suite (https://surfer.nmr.mgh.harvard.edu) was applied to the high-resolution MPRAGE anatomical image. Subsequently, the white-matter mesh is manually corrected for segmentation and topological errors. Grey-matter masks were obtained by growing three layers on top of the white-matter surface and then used as input for pRF mapping analysis.

The first step in the analysis is the creation of pRF models for every point on the visual field. This is done by creating time courses representing the stimulation paradigm, i.e. non-zero, whenever the stimulus is present at a specific position and zero otherwise. These block functions are convolved with the estimated haemodynamic response function of the individual subject. In a second step, every voxel within grey matter is modelled as a two-dimensional Gaussian function on the visual field with parameters x, y for position and σ for width. Optimization of the best-fitting parameter set is obtained for every voxel by minimizing the residual sum-of-squares. Subsequent to the pRF analysis, the visual cortex (V1, V2, V3) was segmented manually based on the individual, functional polar angle maps. All results reported are based on variance explained thresholds of 10%.

In addition, we calculated subject-specific coverage maps (Amano et al., 2009). For this purpose, all estimated two-dimensional Gaussian functions were centered on their respective pRF position, represented by a grey dot. These Gaussians had a height of one at their centre, with a standard deviation equivalent to the pRF size parameter σ fitted during the analysis. For every pixel on the visual field map, the maximum profile of overlapping Gaussians was taken to form the coverage map. As a result, a two-dimensional map, with values between zero and one, was obtained representing the subjects' visual field ("coverage map"). Group-mean coverage maps were obtained by averaging single-subject coverage maps across all subjects.

2.5. Combining coverage maps

Given that the kind of stimulation pattern used in pRF mapping can have effects on the resulting coverage maps, a particular focus of the present study was laid on ways for combining mapping results obtained from different stimulation patterns. This combination can be performed before or after analysis. A straightforward way for pre-analysis combination is concatenating wedge/ring and bar data sets and performing a single analysis on the concatenated data. Here, we introduce an approach where analysis results are combined based on the variance-explained values of the different stimuli runs, i.e. by choosing the model with the highest variance explained in every single voxel. Therefore, every voxel is only represented once and its parameters originate in one of the underlying analyses. In particular, we employed two approaches where the final coverage maps were obtained by choosing the best-fitting model from

1. two coverage maps (“Best of Two”, Bo2): concatenated wedge/ring and concatenated bar stimuli runs
2. four coverage maps (“Best of Four”, Bo4): each individual functional run, i.e. two separate wedge/ring and two separate bar stimulus runs.

3. Results

3.1. Single-run comparison

For all subjects, pRF analyses yielded the expected patterns of eccentricity, polar angle and pRF sizes. Fig. 2 shows coverage maps resulting from wedge/ring and bar runs of a typical subject thresholded at 10% variance explained. It can be seen that while both maps show the pattern expected in a healthy subject, there are marked differences in the distribution of pRF centres across the visual field. Although both coverage maps show similar distributions of pRF centres, closer examination indicates higher pRF centre density in the visual field for wedge/ring stimulation, while bar stimulation yields more homogeneous coverage in peripheral regions.

Similar patterns can be seen in the parameter maps on the visual cortex (Fig. 3). Each row represents a different parameter of the pRF analysis (from top to bottom: eccentricity, polar angle, pRF size, variance explained). Parameters are shown only in voxels where the model explained more than 10% of total variance. In general, all retinotopic parameter maps show the expected distributions, i.e. central parts of the visual field are mapped to the posterior part of V1, polar angle values associated with the horizontal meridian of the visual field are represented on the contralateral calcarine sulcus while values associated with the vertical meridian indicate the borders of V1 and V2 and pRF size increase with eccentricity. However, it can also be seen that the extent of above-threshold results in posterior parts of V1 is higher in wedge/ring compared to bar stimulation runs. In addition, pRF sizes seem generally higher in bar stimulation results.

Comparing the two columns, the wedge/ring stimulus yielded more activated voxels on the occipital pole, whereas the bar stimulus showed better performance in more peripheral areas. These differences in coverage arise from the fact that variance explained values in central regions of the visual field are higher for wedge/ring than bar stimulation.

3.2. Concatenated results

As a first approach for the combination of individual runs, the repeated runs for a given stimulus were concatenated and subsequently analysed as a single run. This doubles the number of time-points and should thus improve model fitting. The corresponding pRF parameter maps for the same subject as shown in Figs. 2 and 3 can be seen in Supplementary Fig. 1. Individual eccentricity maps and coverage maps for wedge/ring and bar results in all ten subjects are shown in Supplementary Fig. 5.

Further, data sets combining wedge/ring and bar runs were obtained by concatenating one single wedge/ring run and one single bar run. This yielded the same run-length as the concatenated single-stimulus analyses and allowed for direct comparisons. This combination is referred to as wedge/ring+bar.

For a direct comparison of wedge/ring and bar coverage map results, visual field coverage plots were averaged across all ten subjects (Fig. 4, top row). The two plots on the top represent concatenated-single-stimulus analyses (either wedge/ring or bar) and show the pattern...
expected from our representative subject. Note that maps were scaled between 0.8 and 1.0 to highlight inhomogeneities. Distinct differences between bar and wedge/ring stimuli can be seen in these group-averaged coverage plots. The bar stimulus shows reduced coverage in the upper meridian while wedge/ring stimulation yields inhomogeneities in the lower meridian. In addition, wedge/ring results indicate slight reductions in the central visual field (<1°).

Average coverage obtained from concatenating wedge/ring and bar runs is given in the central wedge/ring+bar map. It can be seen that concatenating data sets of different stimuli yield maps that resemble logical conjunction of the separate stimulus results. In other words, falling in one model resulted in failure for the combined model. Concatenating combines rather than compensates the deficits in the wedge/ring and bar stimulus maps.

To examine pRF-centre differences between the stimuli further, we calculated the number of voxels associated with specified parts of the visual field surpassing the variance-explained threshold. For this, the visual field-of-view was split into 34 segments (see Fig. 5; ROI numbers printed in italic, percentage differences printed in bold): a foveal part (diameter 4°), two rings (width 2.5°) of 16 segments, each with a width of 22.5°, and one peripheral region (outside 7°). The number of pRF centres within a respective area was added over all ten subjects, and the difference between the two stimulus types was calculated. Hence, negative values (orange/red colour) in Fig. 5 represent areas, where the analysis of the wedge/ring stimulus yielded a higher number of pRF centres than the bar analysis and vice-versa. All calculations were performed for variance-explained thresholds of 1%, 5%, 10% and 20%, respectively.

Here it can be seen, that independent of the threshold applied – bar stimulation yields higher voxel counts in peripheral regions while wedge/ring stimulation results in higher pRF centre numbers in the foveal ROI. Further, the higher the variance-explained threshold, the higher the relative difference in the foveal region.

A notable exception can be seen in the peripheral right visual field-of-view (ROI 18 and 19) where wedge/ring stimulation yielded higher voxel numbers compared to bar stimulation. Of special importance is the fact that this region corresponds to the initial position of the wedge stimulus, strongly indicating a dependency of pRF mapping results on the stimulation patterns used.

Those clear and systematic differences in pRF centre position between stimulus types can also be examined based on direct comparisons of pRF parameters eccentricity, polar angle, pRF size and variance explained. Plots for these parameters including all V1 data points are displayed in Fig. 6. Results for V2 and V3 yielded similar results and are reported in Supplementary Fig. 4. Bar and wedge/ring values are plotted along the x- and y-axis, respectively. Due to the high number of points, initial point clouds were converted to histograms. In addition, isodensity lines (grey) obtained from the initial point cloud are also shown. Points plotted on the 45° line (red) indicate identical result in both analyses.

The upper row represents the two position parameters of the pRF centres, eccentricity (left) and polar angle (right). While polar angles are located close to the red identity line, thus, showing high similarity across wedge/ring and bar results, eccentricity shows a strong systematic bias. In fact, 81% of all eccentricity points are below the red identity line, indicating that the majority of voxels exhibit lower eccentricity with wedge/ring than with bar stimuli.

The third fitting parameter of retinotopic mapping is the pRF size. Corresponding plots for wedge/ring and bar results are shown in the lower left of Fig. 6. Here, 92% of all points are below the red line, again indicating a systematic bias, whereby pRF sizes are considerably smaller in wedge/ring results compared to bar stimulation. Contrasting variance explained values from wedge/ring and bar stimulation (Fig. 6, lower right) shows overall comparable results for the two stimulus types with slightly higher numbers for wedge/ring stimulation.

Plotting pRF sizes for the two stimulus types over eccentricity (Fig. 7) confirms the strong effects of stimulus selection across all visual areas examined. In V1 and V2, pRF sizes from bar stimulation are higher up to 6° eccentricity. For V3, this difference is present up to 2° and changes the sign for eccentricities greater than 4°. It can also be seen that pRF size estimated from bar stimulation runs increases linearly over eccentricity, while wedge/ring-based pRF size shows a more volatile behaviour. Results from concatenated wedge/ring+bar data sets exhibit the lowest pRF size values across the whole eccentricity range. When wedge/ring and bar results are combined in the best-of-4 approach, pRF sizes lie between bar and wedge/ring+bar results.

Fig. 8 shows plots of variance explained values over eccentricity. It can be seen that wedge/ring stimuli yield somewhat better model fit up to about 2°, but drastically worse fitting for eccentricities above 5°. Concatenated wedge/ring+bar data sets result in explained variance values between pure wedge/ring and bar run results.
3.3. Coverage map combination

In order to mitigate stimulus-specific coverage deficiencies, we examined two approaches for combining wedge/ring and bar stimulation results based on maximum explained variance. For each subject, fMRI data of two wedge/ring stimulation runs and two bar stimulation runs are available. While in the Bo2 approach, concatenated wedge/ring and concatenated bar runs were used, Bo4 used all four available runs (two wedge/ring runs, two bar runs). The lower row of Fig. 4 shows the corresponding coverage maps in comparison with the original wedge/ring and bar results. It can be seen that – as expected – combining results across stimulation variants avoids stimulus-specific deficiencies and improves the homogeneity of coverage maps.

In Fig. 9, the combination results are shown for the representative subject. Combining the wedge/ring stimulus’ excellent performance in the central visual field as well as the bar stimulus’ homogeneous pRF coverage in the peripheral visual field yields high-quality mapping results across the whole V1 region.

Averaged across all ten subjects, the number of voxels above the 10% variance-explained threshold shows statistically significant increases when the two stimuli are combined with the novel combination method as it is shown in Table 1, with the significance values in Table 2 obtained from a paired t-test comparing the single stimulus and the combination result. Further, the increased homogeneity of the visual field coverage plots is shown by calculating the plot's mean and standard deviation. In contrast, concatenating wedge/ring and bar data sets before analysis (wedge/ring+bar approach) yields a significantly lower number of voxel counts compared to the single stimulus results.

The selection pattern within the visual field-of-view for the different stimuli, i.e., the stimulus variant yielding higher explained variance values is of special interest. For our representative subject, Fig. 10 shows the voxels labelled by the stimulus variant they originate from...
Fig. 4. Group-average of single-subject visual field coverage. The upper row shows results from the concatenated wedge/ring runs (left) and bar runs (right). Analysing the concatenated wedge/ring and bar runs as single data sets yielded the map shown in the central row (wedge/ring+bar). The bottom row shows averaged coverage maps from the novel combination methods “best of 2” and “best of 4”. Results clearly improve when combining maps, but still, a subtle under-representation along the vertical median is visible in best-of-2 and best-of-4 result variants.

Table 1
Results for the number of above-threshold voxels and average coverage plot mean values averaged across all subjects

| stimulus type | voxels      | mean coverage |
|---------------|-------------|---------------|
| bar           | 12387 ± 1615 | 0.9945 ± 0.0079 |
| wedge/ring    | 12322 ± 2061 | 0.9862 ± 0.0151 |
| wedge/ring+bar | 10555 ± 1482 | 0.9964 ± 0.0153 |
| best of 2     | 12684 ± 1798 | 0.9944 ± 0.0052 |
| best of 4     | 13900 ± 1918 | 0.9945 ± 0.0050 |

for the Bo4 combination, the Bo2 combination is shown in Supplementary Fig. 2. As expected from the variance explained over eccentricity plots (Fig. 8), wedge/ring stimuli yield higher variance explained values for central areas, whereas bar stimuli yield higher variance explained values in peripheral parts of the visual field-of-view. This can also be

Table 2
Absolute differences in mean above-threshold voxels between the stimulus variants. Statistically significant results are marked by asterisks (* p<0.05; ** p<0.001).

| stimulus type | bar     | wedge/ring |
|---------------|---------|------------|
| bar           | -       | +65        |
| wedge/ring    | -65     | -          |
| wedge/ring+bar | -1832** | -1767**    |
| best of 2     | +297*   | +362*      |
| best of 4     | +1513** | +1578**    |
seen on the inflated cortical surface, where anterior regions (i.e. areas representing the peripheral visual field) originate from bar stimulation runs.

To obtain the corresponding group-level distribution, two-dimensional histograms with a bin size of 0.2 by 0.2° were calculated by the count of pRF centres across all ten subjects and normalized to the total number of above-threshold centres.

Fig. 5 shows the resulting distributions across the visual field (orange: wedge/ring stimulus showed maximum explained variance; blue: bar stimulus showed maximum explained variance). In addition, the difference of bar and wedge/ring histograms is displayed in the bottom row of Fig. 11, along with its binarised version (positive values blue, negative values orange). It can be seen that the stimulus preference presented in the representative subject (Fig. 10) is preserved in the group-analysis.
results. While peripheral pRF centre time courses are better modelled with the bar stimulus, foveal pRF centres show higher explained variance with the wedge/ring stimuli. In the binarised map, it can be seen that stimulus preference changes at an eccentricity value of approximately 2°.

4. Discussion

In this study, we have applied two different stimulus variants to pRF mapping: sweeping bar and wedge/ring. We have examined ways for combining pRF maps from different stimuli and have assessed the effects
Fig. 8. **Figure 7:** Average of single-subject results representing variance explained values over eccentricity (width corresponds to the standard error of the mean). Colours represent stimulus combinations.

Fig. 9. **Figure 9:** Single-subject results obtained by combining four single-run results (best of 4) or two concatenated analysis results (best of 2). The combination was performed by voxel-by-voxel selection of the model with the highest variance explained.
of stimulus choice on pRF centre positions, sizes and variance explained distributions. All data were acquired at ultra-high magnetic field (7T) which allowed for increased BOLD sensitivity and specificity compared to 3T studies. Challenges at 7T arising from inhomogeneities in the static magnetic field $B_0$ and excitation field $B_1$ were addressed by high spatial resolution (1mm isotropic) and optimised flip angles (Geissberger et al., 2020; Sladky et al., 2018; Tik et al., 2018). Subjects were young and healthy to ensure continuous attention and excellent fixation stability.

Overall, analyses of pRF data for both stimulus variants showed the expected eccentricity, polar angle and pRF size results. While visual field coverage was generally found uniform, detailed inspection revealed differences in the results obtained from bar and wedge/ring runs.

For identical explained variance thresholds, wedge/ring runs compared to bar stimulus runs show more above-threshold voxels in central regions. This may arise from the fact that the bar stimulus shape is kept constant throughout the visual field, i.e., thickness and speed do not differ between central and peripheral areas. Given that central regions are characterized by high cortical magnification factors and low pRF sizes (Harvey and Dumoulin, 2011), fixed-width bars seem suboptimal to account for the heterogeneity in foveal areas. Contrary, wedge stimulus width increases with eccentricity yielding better model fit in central areas. Following this argument, wedges compared to the bar stimulus cover broader areas in the peripheral visual field and hence perform worse in these regions. From the binarised group-level analysis we find that stimulus variant preference changes at an eccentricity of around 2°.

From these results, it may be inferred that the wedge/ring stimulus is preferable in studies targeting the central visual field up to 2° eccentricity, while the bar stimulus could be advantageous in more peripheral regions. This is of special interest when planning studies with patient populations suffering from particular retinal disease.

Comparing pRF centre numbers for the two stimulus variants across the visual field shows one feature that deviates from the overall pattern. Regions number 3, 18 and 19 located in the right upper visual field show higher pRF centre numbers for wedge/ring compared to bar stimulation over all threshold values examined. No such effect is visible in the corresponding left lower visual field (area 14). The position of the regions affected corresponds roughly to the starting position of the wedge stimulus (displayed in Supplemental Fig. 3). Closer inspection of the wedge stimulus time course shows that there exists considerable overlap between the first and last stimulus frame of the wedge stimulus variant. The overlapping areas are thus stimulated three instead of two times during every wedge stimulus part and this yields advantageous results in terms of the variance explained by the model. These overlapping effects arise from the default implementation of stimulus creation in mrVista. A straightforward approach to avoiding these effects would be to avoid presenting the full wedge at the beginning. This would avoid additional peaks within special areas without affecting the overall coverage of the visual field.

While the effects from the overlap in the start and end position of the wedge stimulus are rather obvious, it is worth noting that other stimulus features, particularly the order of the bar appearances, might also influence the results. The latter could be compensated by randomising
the bar presentation scheme across runs. This would be, however, incompatible with the typical approach of data averaging over runs. From our results, it seems clear that effects from subtle stimulation paradigm features on pRF mapping results are worth evaluating.

Averaged across all single-subject results, maps from bar compared to wedge/ring stimulation show higher mean coverage values and less standard deviation. Bar stimulus results show areas of decreased coverage in the upper part of the visual field, while wedge/ring stimulation exhibits insufficiencies on the lower visual field, both along the vertical median. Such coverage map inhomogeneities were also mentioned in previous studies (Hummer et al., 2018; Ma et al., 2013a; Silson et al., 2018a). It was suggested that large draining veins might be causal to these effects due to altered BOLD signal time courses (Kay et al., 2018; Winawer et al., 2010). In addition to these venous effects, the results of this study suggest that stimulus selection is also a factor as the regions of decreased coverage differ between the two stimulus variants.

The combination of data by concatenating wedge/ring and bar runs prior to analysis as done with the wedge/ring+bar approach yielded inferior results compared to single stimulus analyses, both in terms of visual field coverage and number of above-threshold voxels. These somewhat counter-intuitive results can be explained by the considerable differences in pRF size and eccentricity estimates obtained from the two stimulus variants. In particular, fitting results from concatenated wedge/ring and bar run time courses showed the lowest pRF sizes across all stimulus combination approaches investigated.

As a proposed solution for compensating the stimulus-specific coverage map insufficiencies and the low performance of the wedge/ring+bar approach, we suggested a novel method for the combination of the different stimuli. As four pRF mapping runs were acquired in each subject (two wedge/ring runs, two bar runs), we tested two combination approaches: Bo2 based on the results from concatenated wedge/ring and bar runs and Bo4 based on the four individual single-run results. We found that combining pRF mapping data improved coverage maps, with Bo4 yielding the most homogeneous coverage map results. While it is not surprising that coverage maps generally improve by combining pRF mapping results across runs, our data shows that stimulus-specific deficits

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**Fig. 11.** Group-averaged normalized histograms across all ten subjects corresponding to the visual stimulus variant resulting in the maximum explained variance values (blue: bar stimulus, orange: wedge/ring stimulus). The bottom row shows the differences between the two histograms (left: continuous colour scale; right: binarised colour scale). All values are given in percent, respective to the overall number of voxels.
in visual field coverage may be effectively compensated with the approaches proposed.

Direct comparison of variance explained over eccentricity for wedge/ring and bar stimuli demonstrated the features of the novel combination method. While the variance explained is higher with the wedge/ring stimulation in the central visual field the lines cross at an eccentricity slightly above 2° with the bar yielding higher values in more peripheral regions. Remarkably, this closely corresponds to the eccentricity value where the thickness of the bar and the wedge match at 2.1° eccentricity, for the stimulus designs used in this study. The pRF size also shows significant differences. The bar results in a linear distribution over the eccentricity, while the wedge/ring shows a stronger slope in the central visual field and a huge increase in more eccentric areas. This suggests, that the width of the bar is too big to precisely measure the pRF sizes in the visual field and therefore it is impossible for the analysis to find smaller sizes in that area. In contrast, the wedge allows for a much smaller and therefore more specific investigation of the central visual field with the downside of very specific mapping in the more peripheral regions. This leads to a surge in pRF size and a drop in variance explained in the peripheral regions. Single-subject results are similar to the shown group average results and are therefore not explicitly reported.

This study was performed in young, healthy subjects. While we would expect similar results in subjects younger or older compared to the group included in this study, pRF scanning in these groups always comes with additional challenges including sleepiness, motion, gaze stability or even segmental performance.

The stimulus variants applied in this study were selected because of their extensive use across the retinotopic mapping community. Other publications have suggested other stimulus patterns for retinotopic mapping including scaled bar stimuli, where the thickness changes logarithmically with the eccentricity, and simultaneously presented wedge and ring stimuli (Alvarez et al., 2015; Infantini and Schwarzkopf, 2020; van Dijk et al., 2016).

All experiments in this study were performed at an ultra-high magnetic field (7T). Compared to 3T, acquisition at 7T has the main benefit of higher sensitivity and specificity in the activation maps obtained (Olman et al., 2011; Sladky et al., 2013). Such changes in noise levels will influence the extent of activated regions at a given threshold level (e.g. 10% explained variance). As the results of this study are based on direct, pairwise comparisons of wedge/ring and bar stimuli at identical threshold levels, we may expect similar conclusions at 3T.

All stimulus comparisons are heavily influenced by non-controllable circumstances like subject attention or movement. Therefore, further research should establish a theoretical framework for the classification of retinotopic stimuli, in order to rate stimuli more objectively and further enable the design of optimal stimuli for the sampling of specific visual field regions.

5. Conclusion

Coverage maps, eccentricity values and pRF sizes obtained from wedge/ring or bar stimulation runs show systematic differences. Wedge/ring stimuli result in reduced coverage of the lower peripheral visual field, while bar stimulus maps lack areas along the upper peripheral meridian. In addition, wedge/ring stimulation results show lower eccentricity values and strongly reduced pRF sizes compared to bar stimulation runs. The herein proposed method for combining wedge/ring and bar stimulus coverage maps allows compensating these stimulus-specific insufficiencies. We showed that coverage maps obtained by combining both stimulus variants yielded more homogenous coverage throughout the visual field. Direct comparison showed that wedge/ring stimuli provided better model fitting performance for central regions of the visual field, while bar stimulation yielded better results in the peripheral visual field.

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Data and code availability statement

All anonymized data and analysis codes are available upon request in accordance with the requirements of the institute, the funding body, and the institutional ethics board.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.neuroimage.2021.118240.

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