Pre-registered report: Space Sequence Synesthesia Diagnostic using form mapping

2025-11-06

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1 Abstract:

Existent diagnostic tools for space sequence synethesia are based on questionnaire and response consistency. Consistency is calculated as the area between repetitions for the same inducer. In the first present phase, available data from 467 participants is used to explore new geometrical features to discriminate syntheses from controls. Conceptually, our goal is to take advantage of the inducer's ordinality that create synesthetic forms. For this aim, we harness a geography package to extract geometrical features to use as a test for synethesia. Reciever Operator Characteristics are used to select the features that best diagnose synesthesia. In a second phase to come, we test the predictive power of the new diagnostic features onto newly collected dataset.

2 Introduction

Humans with Sequence Space Synesthesia (SSS) represent ordered sequences in particular spatial positions. For example, August (i.e. the *inducer)* might be represented in the bottom left position (i.e. the position is here the *concurrent),* this position is relative to the concurrent position of the other months which could form a circle all together. In addition time units, numbers also take particular forms (Galton 1880), not to be confused with the Mental Number Line [Dehaene to be found]. These forms are idiosyncratic, meaning they might vary across individuals. This makes it difficult to detect authentic SSS and therefore give precise estimates of prevalence in the population. Estimated prevalence for SSS in the general population spans between 4.4 % (Brang et al. 2013) and 14.2 % (Seron et al. 1992), see also (Ward et al. 2018; Sagiv et al. 2006). Hence a reliable diagnostic tool to detect SSS would also be useful to investigate SSS.

Diagnostic depends on the definition of the conditions under investigation. A strict definition of Synestheesia requires five different criteria (Deroy and Spence 2013). *Automaticity*: the *inducer* automatically triggers the *concurrent.* For example august might automatically trigger it's specific spatial location. *Unidirectionality*: while the *inducer* triggers the concurrent, the concurrent does not trigger the inducer. Hence the bottom left position doe not trigger August. *Consciousness*: The concurrent is consciously percieved. *Developmentally early*: the experience was already present during childhood. *Consistency*: the inducer-concurrent pair remains stable in time. For example, August triggers the same bottom left position. Consistency is arguably the most suited criteria to develop a diagnostic tool since it is relatively simple to implement in a behavioral task and quantify.

Hence given consistency, similar concurrent responses triggered by the same inducers can be used as a marker for authentic SSS. Consistency test have become golden standart for colour-grapheme synesthesia, where an inducer is presented (i.e. letters of the alphabet) and the participant is requested to selected the concurrent colour, using a colour picker. Individual consistency is then calculated as the distance between repeated colour responses to the same inducers. Interestingly, the best colour space to detect colour-grapheme synesthesia is CIE*LUV, a colour space developed to be isoform to human perception (Rothen et al. 2013). Analogously to grapheme-colour synesthetes, consistency test can be used to diagnose SSS. In that tasks, it is repeatedly asked to report the position of the inducers on a screen. The total area between the responses of same inducer (i.e. a triangle if repeated three times) is then used as characteristic to diagnose SSS. The rationale being that consistent responses would lead to smaller area than inconsistent ones (Rothen et al. 2016). This method resembles how number forms are describe in the single case study (Piazza, Pinel, and Dehaene 2006), see Experiment 1.

However characterizing synesthetes from non synesthetes using total area has several limitations. For example high consistency by non-synesthetes can be achieved by giving all responses on the same screen position (i.e. false positive). Moreover, this kond of criteria might bias the

diagnosis to include synesthetes with straigth lines which leads to less variability than more complex forms(**?**).

The goal of the present registered report is to first identify new features characterizing synesthetes responses based on already available datasets and test the best working features on a future dataset. The new features are desgined to take advantage of two properties of synesthetic responses that have not been included in precedent consistency tests. First, sequentiality on top of single inducer responses the ordered position between subsequent induces is important. For example the relative position of August and the other months. From numerical cognition, ordinality has been aknowledged to be an important semantic property of numbers, also given their sequential acquisition (i.e. 1 is learned before 2). Second, thee particular synthetic forms of the sequential spatial location. These forms might have geometrical properties. For example months of the year might be represented circularly (as already described by (Galton 1880) for numbers).

To take advantage of sequential and geometrical synesthetic forms, we harnessed a geo-spatial package(Pebesma 2018) to extract geometrical features from participant x and y coordinate responses. This packages allows for example to build string or polygons for each repetition and compare different geometrical features. Those individual geometrical features are then compared using Receiver Operator Charactheristics (ROC) between individuals grouped as synesthes and control. In the present *phase I*,we compare ROC on three merged derivation-datasets using the same task on SSS Ward (n.d.). In future *phase II*, we compare whether the features selected to diagnose SSS in *phase I,* on a validation dataset that is not yet acquired (registered report on the open science foundation: https://osf.io/9efjb/**).**

3 Methods

Phase I: present analyses. First, we reproduce the diagnostic criteria of each respective dataset. Second, we merge the dataset and compare the diagnostic criteria across datasets using Reciever Operator Charachteristics (ROC). Third, we compare wheter the featuers lead to somilar ROC charachteristics across the different sets (i.e. for months, weeks and numbers). Fourth, we compute new candidate geometrical features that could be used to diagnose SS. Finally we summarize and compare all ROC and select the best features that class synesthetes from control with the merged dataset.

Phase II: future analyses. On a future dataset using the same task, we will compare the predictive power of the selected features using ROC.

3.1 Materials

A the exception of (Rothen et al. 2016) (see https://osf.io/6hq94/files/osfstorage), the data from (Ward, n.d.; Van Petersen et al. 2020a) were collected online. The 29 inducers were: the

12 months of a year, 7 days of the week and 10 numbers (i.e. hindo-arabic numerals from 0 to 9). (Van Petersen et al. 2020a) Also presented 50 and 100 numerals, which we excluded here. (Ward, n.d.) data is collected using the Syntoolkit.

3.2 Procedure

The details for each procedure is described in each respective article (Rothen et al. 2016; Ward, n.d.; Van Petersen et al. 2020a), here we describe the common task.

Each participant is presented with one one inducer at a time at the center of a otherwise white screen. The participant is instructed to click at the screen position that they visualize them. Inducers order is randomized and each inducer is repeated three times.

The order of the stimuli was randomised, but such that no stimulus was repeated until the previous batch of unique stimuli (N = 29) had been presented.

4 *Phase I* Methods

The data for *phase I,* comes from: (Rothen et al. 2016),(Ward, n.d.) (from: https://osf.io/p5xsd/files/osfstorage) and (Van Petersen et al. 2020b)

- Root (Root et al. 2021)

```
[1] 0
```

```
# A tibble: 2 x 2
  group     n
  <fct> <int>
1 Ctl      72
2 Syn      12
```

4.1 *Phase I.* Population

dataSource	Ctl	Syn
PeterCor	21	12
Rothen	37	33
Ward	215	252

4.2 *Phase I.* Analysis

First, we replicate consistency methods found in the literature using the same task ((Rothen et al. 2016; Ward, n.d.; Van Petersen et al. 2020a; Root et al. 2021)) and compare the results.

Second, we extract features based on the form. (C) We harness a geography package to compute segment based features (D) We compute polygon based features. (E) Convex Hull (F) Angles.

5 *Phase I.* Results Reproduce

6 Replicated features

6.1 Standart deviation

6.2 Triangle area Consistency

Definition: Calculating consistency Each stimulus is represented by three xy coordinates - (x1, y1), (x2, y2), (x3, y3) - from the three repetitions. For each stimulus, the area of the triangle bounded by the coordinates is calculated as follows:
$Area = (x1y2 + x2y3 + x3y1 - x1y3 - x2y1 - x3y2)/2$

```
`summarise()` has grouped output by 'ID'. You can override using the `.groups`
argument.
```

```
Warning in rm(tmp_perID): object 'tmp_perID' not found
```

7 *Phase I.* Results: Novel features

7.1 Segment self-intersection

The first feature is self-intersections. For each condition and repetition separately, we count how many times the segments self-intersects. Then we average across conditions and repetitions to have one value per subject. Hence the value represents the average number of self-intersections per segment a subject has.

7.2 Segments (with sf)

We will take advantage of the `sf` package and connect the x and y coordinates of ordered inducer with a segment. Sf hates NaN's. Either convert them to 0 (as originally) or remove them. I'll start converting to 0.

```
Linking to GEOS 3.13.0, GDAL 3.8.5, PROJ 9.5.1; sf_use_s2() is TRUE
```

```
Spherical geometry (s2) switched off
```

```
Warning: Using one column matrices in `filter()` was deprecated in dplyr 1.1.0.
i Please use one dimensional logical vectors instead.
```

7.2.1 Segment length (should replicate Rothen)

8 Distances between repetitions

8.1 Polygon based geometries

8.1.1 Polygon area

9 Polygon simplicity

10 Topological validity Structure

is topologically valid:

From the package description: *"For projected geometries, st_make_valid uses the lwgeom_makevalid method also used by the PostGIS command ST_makevalid if the GEOS version linked to is smaller than 3.8.0, and otherwise the version shipped in GEOS; for geometries having ellipsoidal coordinates s2::s2_rebuild is being used."* From https://postgis.net/docs/ST_IsValid.html: *value is well-formed and valid in 2D according to the OGC rules.* (Open Geopsatial Consotrtium)

10.1 is clockwise

10.2 Convex Hull Area

11 Compare all features:

11.1 Compute all ROC

```
                  [,1]               [,2]            [,3]                  [,4]
feature_list      "SD_ID_xsc" "SD_ID_ysc" "triangle_area_GA" "Consistency_zs"
feature_direction "moreSyn"    "moreSyn"    "moreCtl"          "moreCtl"
                  [,5]                 [,6]            [,7]            [,8]
feature_list      "SelfInter_persegm" "GA_segm_leng" "GA_BtwDist" "GA_areaPoly"
feature_direction "moreCtl"            "moreCtl"       "moreCtl"    "moreSyn"
                  [,9]              [,10]                [,11]
feature_list      "GA_isSimple" "Sum_isValidStruct" "GA_isValidStruct"
feature_direction "moreSyn"       "moreSyn"            "moreSyn"
                  [,12]               [,13]
feature_list      "Sum_isClockwise" "GA_area_convhull"
feature_direction "moreSyn"          "moreSyn"


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```

12 Summaries

12.1 Summary table:

	Feature	AUC	threshold	sensitivity	specificity	ppv	npv	ci_low	ci_high
9	Sum_isValidStruct	77.85	1.50	70.71	75.46	75.81	70.31	74.12	81.57
10	GA_isValidStruct	77.85	0.17	70.71	75.46	75.81	70.31	74.12	81.57
4	SelfInter_persegm	74.26	1.17	79.46	62.64	69.82	73.71	70.13	78.38
7	GA_areaPoly	70.91	1.29	60.61	70.70	69.23	62.26	66.72	75.11
3	Consistency_zs	69.81	2.22	76.43	64.84	70.28	71.66	65.22	74.40
8	GA_isSimple	68.78	0.28	60.94	69.60	68.56	62.09	64.46	73.10
1	SD_ID_ysc	68.68	0.12	80.81	59.71	68.57	74.09	64.13	73.22
5	GA_segm_leng	63.07	7.86	83.84	48.72	64.01	73.48	58.34	67.81
11	Sum_isClockwise	61.73	2.50	76.09	41.76	58.70	61.62	57.19	66.27
6	GA_BtwDist	57.90	0.03	96.30	26.74	58.85	86.90	53.68	62.12
12	GA_area_convhull	56.88	1.49	76.77	48.35	61.79	65.67	51.96	61.80
2	triangle_area_GA	49.26	2338.97	76.09	38.83	57.51	59.89	44.27	54.25

12.2 Summary plot

```
Warning: Using `size` aesthetic for lines was deprecated in ggplot2 3.4.0.
i Please use `linewidth` instead.
```
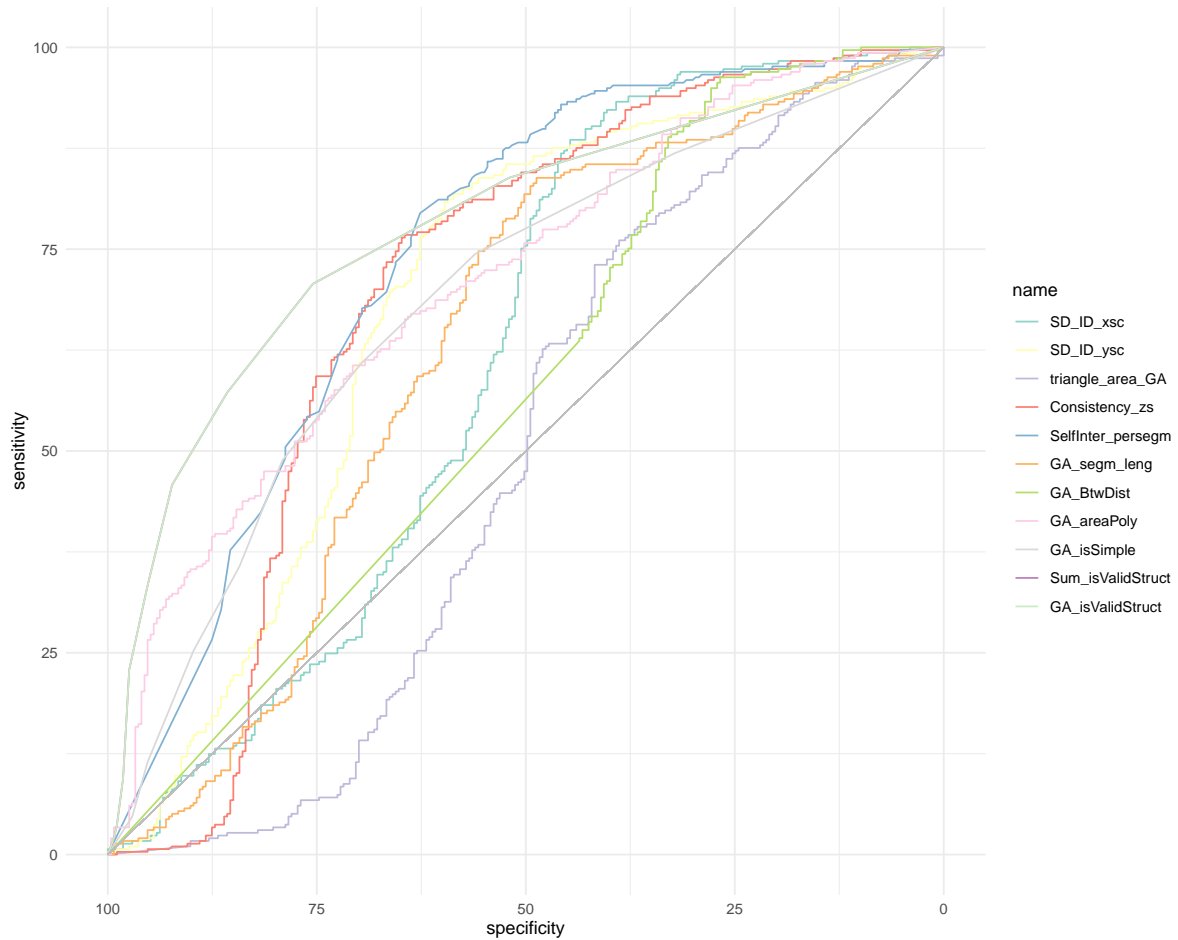
12.3 Summary contingency:

```
[1] "SD_ID_xsc"

       Test : Ctl     Test : Syn
  Ctl "122 (44.7%)" "151 (55.3%)"
  Syn "34 (11.4%)"  "263 (88.6%)"
[1] "SD_ID_ysc"

       Test : Ctl     Test : Syn
  Ctl "163 (59.7%)" "110 (40.3%)"
  Syn "57 (19.2%)"  "240 (80.8%)"
[1] "triangle_area_GA"
```

```
     Test : Ctl    Test : Syn
Ctl "106 (38.8%)" "167 (61.2%)"
Syn "71 (23.9%)"  "226 (76.1%)"
[1] "Consistency_zs"

     Test : Ctl    Test : Syn
Ctl "177 (64.8%)" "96 (35.2%)"
Syn "70 (23.6%)"  "227 (76.4%)"
[1] "SelfInter_persegm"

     Test : Ctl    Test : Syn
Ctl "171 (62.6%)" "102 (37.4%)"
Syn "61 (20.5%)"  "236 (79.5%)"
[1] "GA_segm_leng"

     Test : Ctl    Test : Syn
Ctl "133 (48.7%)" "140 (51.3%)"
Syn "48 (16.2%)"  "249 (83.8%)"
[1] "GA_BtwDist"

     Test : Ctl    Test : Syn
Ctl "73 (26.7%)" "200 (73.3%)"
Syn "11 (3.7%)"  "286 (96.3%)"
[1] "GA_areaPoly"

     Test : Ctl    Test : Syn
Ctl "193 (70.7%)" "80 (29.3%)"
Syn "117 (39.4%)" "180 (60.6%)"
[1] "GA_isSimple"

     Test : Ctl    Test : Syn
Ctl "190 (69.6%)" "83 (30.4%)"
Syn "116 (39.1%)" "181 (60.9%)"
[1] "Sum_isValidStruct"

     Test : Ctl    Test : Syn
Ctl "206 (75.5%)" "67 (24.5%)"
Syn "87 (29.3%)"  "210 (70.7%)"
[1] "GA_isValidStruct"

     Test : Ctl    Test : Syn
Ctl "206 (75.5%)" "67 (24.5%)"
Syn "87 (29.3%)"  "210 (70.7%)"
```

```
[1] "Sum_isClockwise"

      Test : Ctl    Test : Syn
  Ctl "114 (41.8%)" "159 (58.2%)"
  Syn "71 (23.9%)"  "226 (76.1%)"
[1] "GA_area_convhull"

      Test : Ctl    Test : Syn
  Ctl "132 (48.4%)" "141 (51.6%)"
  Syn "69 (23.2%)"  "228 (76.8%)"
```

12.4 Summary excluding overlapping responses

```
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Setting levels: control = Ctl, case = Syn
```

	Feature	AUC	threshold	sensitivity	specificity	ppv	npv	ci_low	ci_high
3	Consistency_zs	76.08	2.22	76.84	70.65	78.78	68.27	71.49	80.67
8	GA_isSimple	75.92	0.28	60.70	80.60	81.60	59.12	71.70	80.13
9	Sum_isValidStruct	75.38	1.50	73.33	67.16	76.00	63.98	71.13	79.64
10	GA_isValidStruct	75.38	0.17	73.33	67.16	76.00	63.98	71.13	79.64
5	GA_segm_leng	71.20	7.86	83.51	62.69	76.04	72.83	66.15	76.25
4	SelfInter_persegm	67.85	1.17	82.11	49.25	69.64	66.00	62.89	72.80
7	GA_areaPoly	64.78	1.92	41.05	83.08	77.48	49.85	59.90	69.66
1	SD_ID_ysc	61.49	0.11	84.21	44.28	68.18	66.42	56.11	66.88
2	triangle_area_GA	60.27	2124.47	72.28	53.23	68.67	57.53	54.88	65.65

	Feature	AUC	threshold	sensitivity	specificity	ppv	npv	ci_low	ci_high
11	Sum_isClockwise	54.22	6.50	20.00	91.04	76.00	44.53	49.14	59.29
6	GA_BtwDist	54.03	0.03	97.54	17.41	62.61	83.33	49.40	58.66
12	GA_area_convhull	45.45	1.49	78.60	32.34	62.22	51.59	39.93	50.96

13 Combination ROC

Setting levels: control = Ctl, case = Syn

Setting direction: controls < cases

Call:
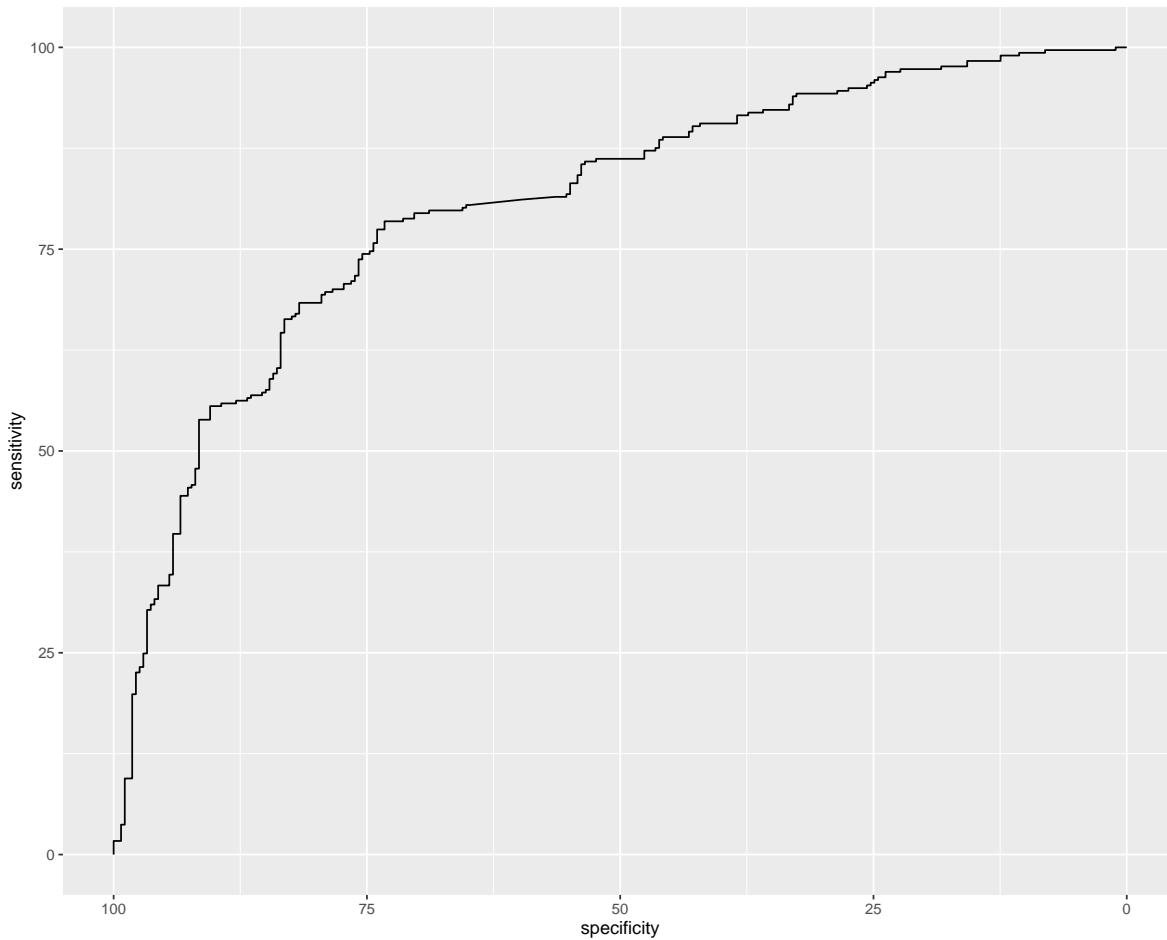roc.default(response = ds_Q$group, predictor = ds_Q$Comb)

Data: ds_Q$Comb in 273 controls (ds_Q$group Ctl) < 297 cases (ds_Q$group Syn).
Area under the curve: 0.8055

Setting levels: control = Ctl, case = Syn

```
  Feature    AUC threshold sensitivity specificity      ppv      npv   ci_low
1    Comb 80.5497 -0.188664    78.45118    73.26007 76.14379 75.75758 76.97065
   ci_high
1 84.12875
```

Setting levels: control = Ctl, case = Syn

```
Setting levels: control = Ctl, case = Syn
Setting direction: controls < cases




Call:
roc.default(response = ds_Q2$group, predictor = ds_Q2$Comb)

Data: ds_Q2$Comb in 201 controls (ds_Q2$group Ctl) < 285 cases (ds_Q2$group Syn).
Area under the curve: 0.7967


Setting levels: control = Ctl, case = Syn


  Feature     AUC threshold sensitivity specificity      ppv      npv   ci_low
1    Comb 79.6701 0.1209209    79.64912    67.16418 77.4744 69.94819 75.66566
```
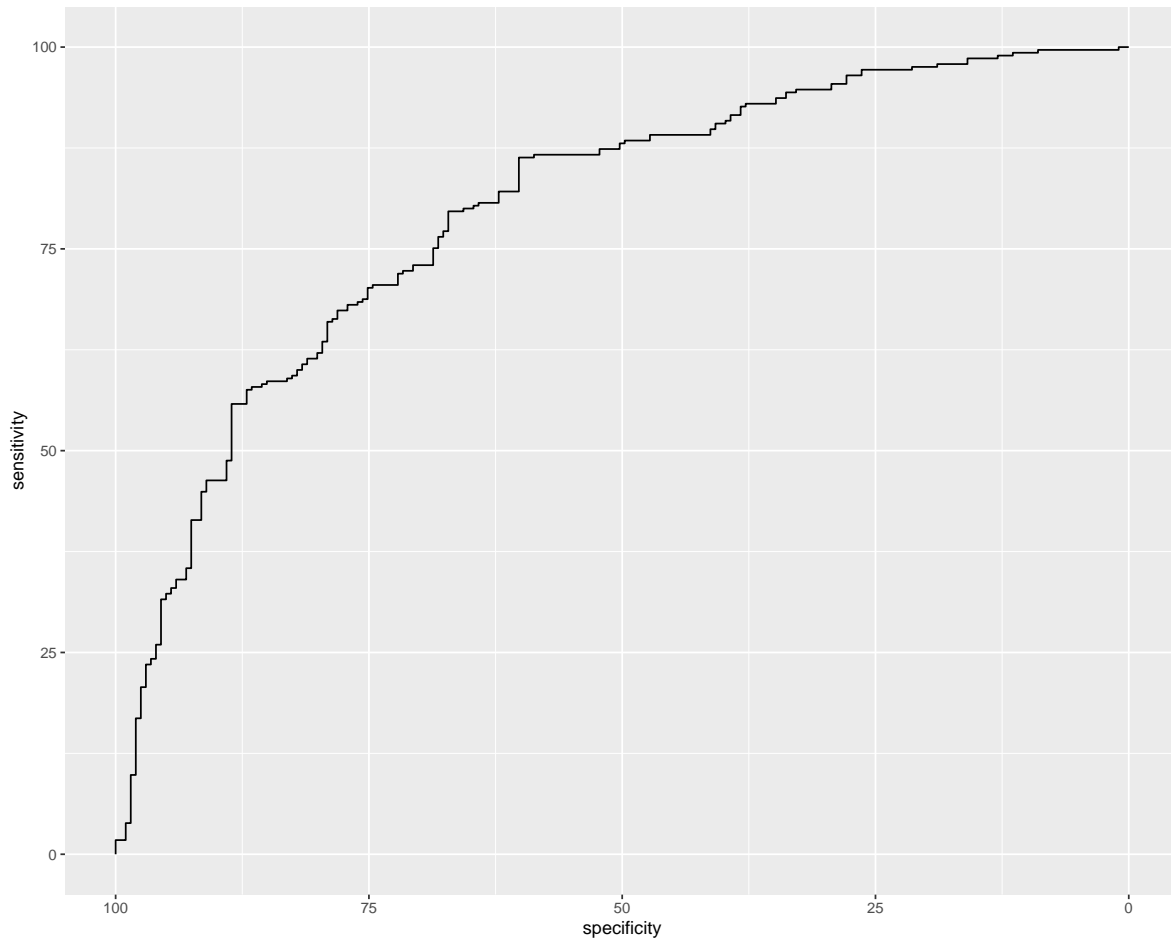
```
   ci_high
1 83.67448
```

Setting levels: control = Ctl, case = Syn
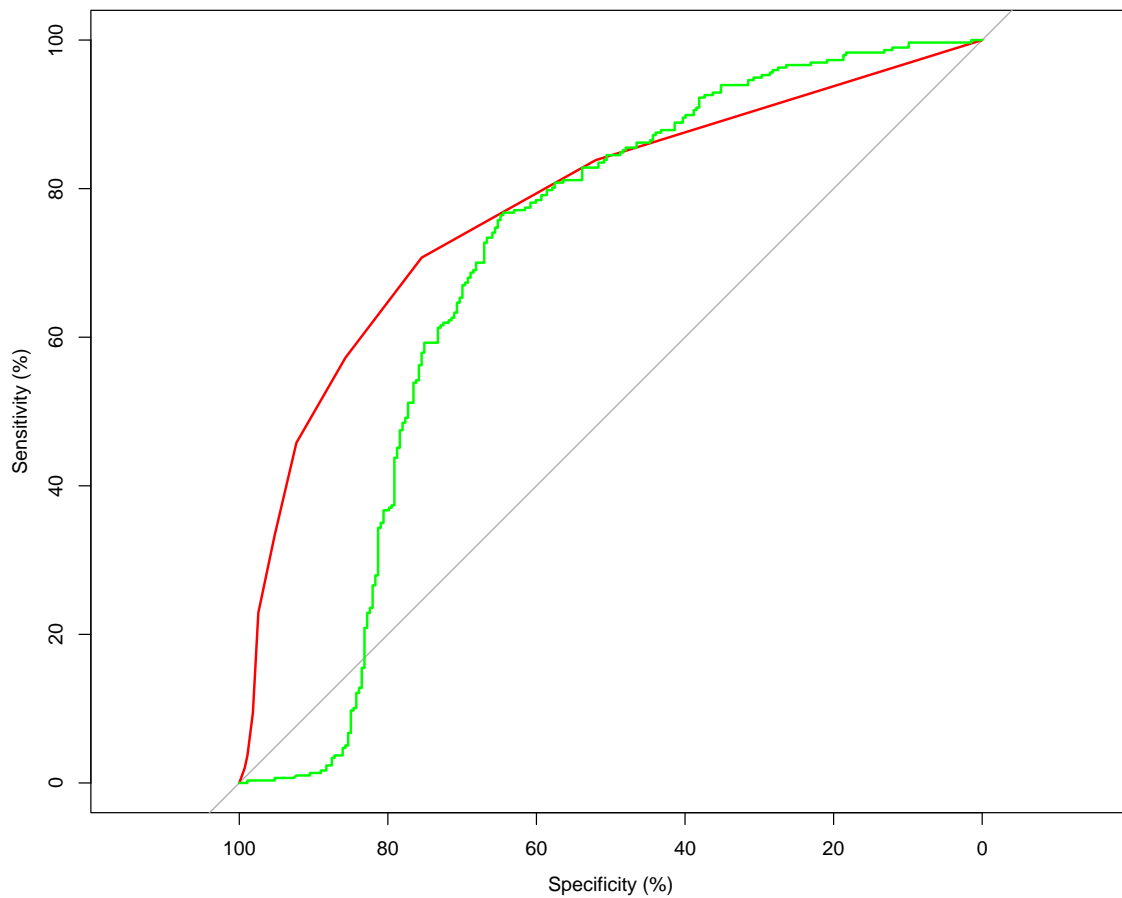

14 Could compare each feature singularly:

Setting levels: control = Ctl, case = Syn

Setting direction: controls < cases

Setting levels: control = Ctl, case = Syn

Setting direction: controls > cases
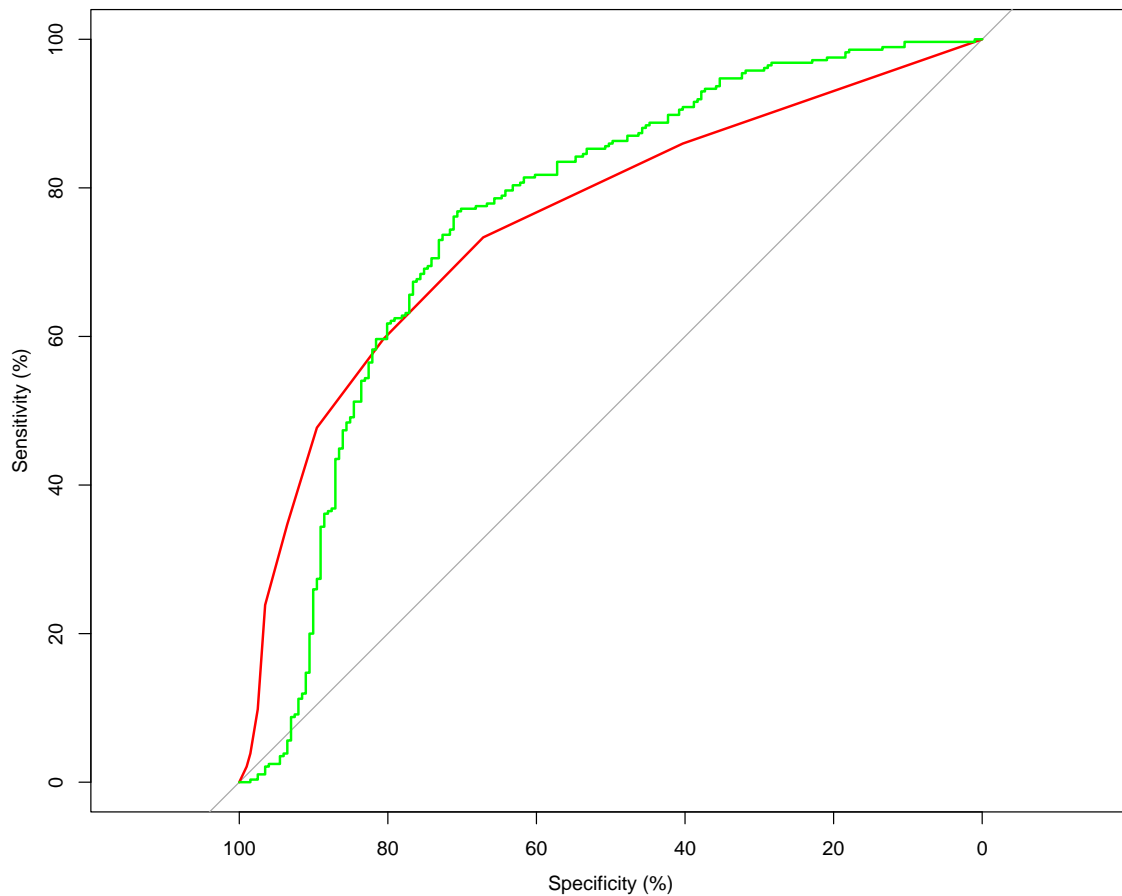


```
    Bootstrap test for two correlated ROC curves

data:  ROC_Valid and ROC_Cons
D = 2.8691, boot.n = 2000, boot.stratified = 1, p-value = 0.004116
alternative hypothesis: true difference in AUC is not equal to 0
sample estimates:
AUC of roc1 AUC of roc2
   77.84623    69.80982


Setting levels: control = Ctl, case = Syn
```

```
Setting direction: controls < cases

Setting levels: control = Ctl, case = Syn

Setting direction: controls > cases
```



```
        Bootstrap test for two correlated ROC curves

data:  ROC_Valid and ROC_Cons
D = -0.26343, boot.n = 2000, boot.stratified = 1, p-value = 0.7922
alternative hypothesis: true difference in AUC is not equal to 0
sample estimates:
AUC of roc1 AUC of roc2
   75.38448     76.07576
```

14.1 *Phase II* Methods

14.2 *Phase II* Materials:

Materials are desribed here https://osf.io/pjb6e/?view_only=d467ebf4c1f94076ae4ac61298255065.

14.3 *Phase II* Planned population

https://osf.io/6h8dx

15 Discussion

From the different features we extracted, topological validity across the repetitions appeared to be the one leading to the largest Area Under the Curve. The optimal cutoff was exactly 1.5, leading to a sensitivity () and specificity ().

The optimal criterion ineeds to be informed about the order between inducers (i.e. to construct the polygons) and interestingly suggests that synthetic inducer are structurally mapped following topological rules analogous to geographical space structures. Hence suggesting a spatial nature for the synthetic forms of space sequence synesthetes.
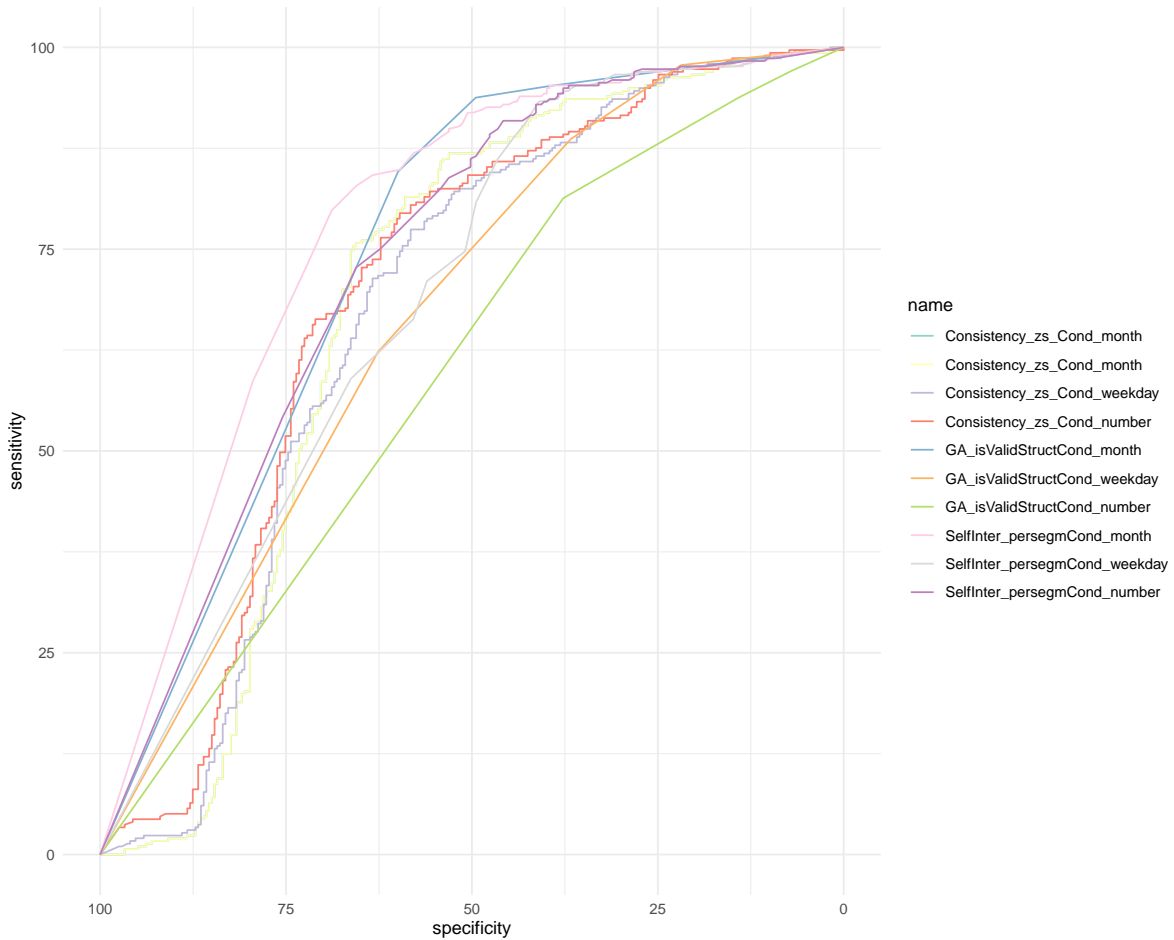
16 Supplementary: Conditions

16.1 Per Conditions

```
Warning in rm(ROC_curvesCond): object 'ROC_curvesCond' not found


Setting levels: control = Ctl, case = Syn
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Setting levels: control = Ctl, case = Syn


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Setting levels: control = Syn, case = Ctl
Setting levels: control = Syn, case = Ctl


Setting levels: control = Ctl, case = Syn
Setting levels: control = Ctl, case = Syn
Setting levels: control = Ctl, case = Syn
```

sensitivity (y-axis) vs specificity (x-axis)

name
- Consistency_zs_Cond_month
- Consistency_zs_Cond_month
- Consistency_zs_Cond_weekday
- Consistency_zs_Cond_number
- GA_isValidStructCond_month
- GA_isValidStructCond_weekday
- GA_isValidStructCond_number
- SelfInter_persegmCond_month
- SelfInter_persegmCond_weekday
- SelfInter_persegmCond_number

16.2 Summary table Per cond

	Feature	AUC	threshold	sensitivity	specificity	ppv	npv	ci_low	ci_high
7	SelfInter_persegmCond	77.82730	100.00000	79.79798	68.86447	73.60248	75.80645	77.20136	78.45410
4	GA_isValidStructCond	74.26340	1.16667	84.61538	59.93266	66.00000	80.90909	72.26509	76.26170
9	SelfInter_persegmCond	73.23232	5.00000	72.72727	65.56777	69.67742	68.84615	72.49721	73.96743
3	Consistency_zs_Cond	69.80660	0.733664	79.46128	59.70696	68.20809	72.76784	68.47900	70.13424
8	SelfInter_persegmCond	68.60421	5.00000	93.26599	41.02564	63.24201	84.84848	67.69484	69.51363
1	Consistency_zs_Cond	68.26011	0.737657	75.42088	65.93407	70.66246	71.14625	67.47714	69.04313
2	Consistency_zs_Cond	67.05090	0.539942	77.44108	58.24176	66.86047	70.35398	66.03741	68.06429
5	GA_isValidStructCond	66.65563	5.00000	88.64469	36.70034	56.27907	77.85714	64.31845	68.99268
6	GA_isValidStructCond	59.67480	1.66667	81.31868	37.71044	54.54545	68.71166	57.57482	61.77373

19

17 Graph

```
Warning: `stat(quantile)` was deprecated in ggplot2 3.4.0.
i Please use `after_stat(quantile)` instead.
```

```
Picking joint bandwidth of 0.0509
```
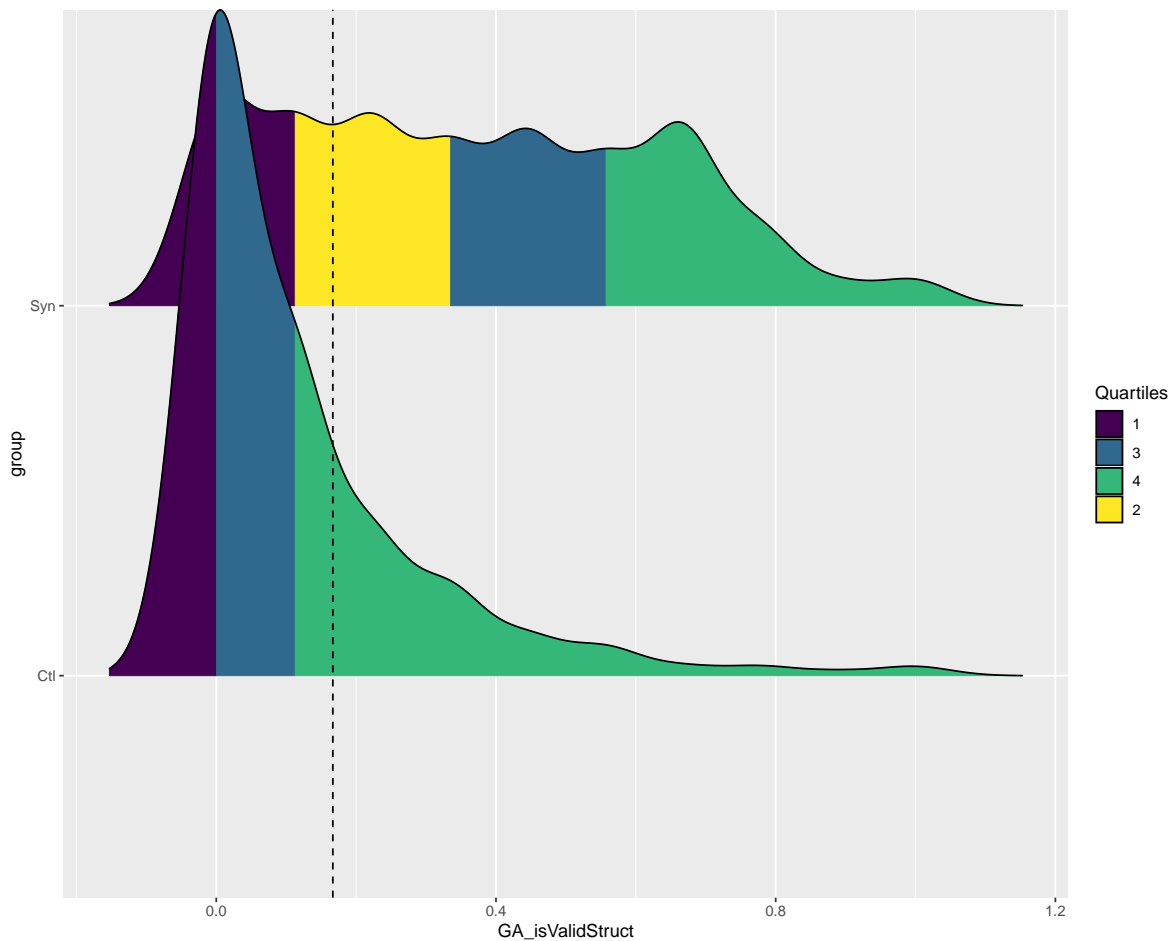

References

Brang, David, Luke E. Miller, Marguerite McQuire, V. S. Ramachandran, and Seana Coulson. 2013. "Enhanced Mental Rotation Ability in Time-Space Synesthesia." *Cognitive Processing* 14 (4): 429–34. https://doi.org/10.1007/s10339-013-0561-5.

Deroy, Ophelia, and Charles Spence. 2013. "Why We Are Not All Synesthetes (Not Even Weakly So)." *Psychonomic Bulletin & Review* 20 (4): 643–64. https://doi.org/10.3758/s13423-013-0387-2.

Galton, Francis. 1880. "Visualised Numerals." *Nature* 21 (533): 252–56. https://doi.org/10.1038/021252a0.

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