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1 ***SARA captures disparate progression and responsiveness in spinocerebellar ataxias***

2

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29

30 **ABSTRACT**

31 **Background:** The Scale for Assessment and Rating of Ataxia (SARA) is a widely used clinical scale to assess  
32 cerebellar ataxia but faces some criticisms about the relevancy of all its items.

33 **Objectives:** To prepare for future clinical trials, we analyzed the progression of SARA and its items in several  
34 polyQ spinocerebellar ataxias (SCA) from various cohorts.

35 **Methods:** We included data from patients with SCA1, SCA2, SCA3, and SCA6 from four cohorts (EUROSCA,  
36 RISCA, CRC-SCA, and SPATAX) for a total of 850 carriers and 3431 observations. Longitudinal progression of  
37 the SARA and its items was measured. Cohort, stage and genetic effects were tested. We looked at the respective  
38 contribution of each item to the total scale. Sensitivity to change of the scale and the impact of item removal was  
39 evaluated by calculating sample sizes needed in various scenarios.

40 **Results:** Longitudinal progression was significantly different between cohorts in SCA1, SCA2 and SCA3, the  
41 EUROSCA cohort having the fastest progression. Advanced stage patient were progressing slower in SCA2 and  
42 SCA6. Items were not contributing equally to the full scale through ataxia severity: gait, stance, hand-movement,  
43 and heel-shin contributed the most in early stage, and finger-chase, nose-finger, and sitting in later stages. Few  
44 items drove the sensitivity to change of SARA, but changes in the scale structure could not improve its  
45 sensitivity in all populations.

46 **Conclusion:** SARA and its items progression pace showed high heterogeneity across cohorts and SCAs.  
47 However, no combinations of items improved the responsiveness in all SCAs or populations taken separately.

48 3794 words

49 **INTRODUCTION**

50 Autosomal dominant cerebellar ataxias of type 1, 2, 3, and 6, also known as spinocerebellar ataxias (SCA1, 2, 3,  
51 and 6), are clinically heterogeneous neurodegenerative diseases. They are caused by (CAG)<sub>n</sub> repeat expansions  
52 in the *ATXN1*, *ATXN2*, *ATXN3*, and *CACNA1A* genes respectively, resulting in the expansion of a polyglutamine  
53 tract in the corresponding proteins (Coarelli et al., 2023; Durr, 2010). SCAs are rare diseases, with a global  
54 prevalence of 0.0 to 5.6 per 100,000 (Ruano et al., 2014). The number of CAG repeats determines disease carrier  
55 status, the threshold between what is considered a pathological or a normal size varies for each SCA, and the  
56 longer the repeats in the expansion the earlier the age at onset (Tezenas du Montcel et al., 2014), and the faster  
57 the disease in SCA1 and SCA2 (Jacobi et al., 2011).

58 In the context of readiness for clinical trials in SCAs, there is a need to understand the natural history over the  
59 individual course of disease to refine the inclusion criteria for potential treatments. Cerebellar ataxia (including  
60 signs and symptoms) is clinically progressive over the disease course, considered to reflect the progression of the  
61 underlying pathology of SCA and it can be assessed using the Scale for Assessment and Rating of Ataxia  
62 (SARA) (Schmitz-Hubsch et al., 2006). A previous meta-analysis already studied the progression of the SARA  
63 for these 4 SCA subtypes in different cohorts to estimate the annual progression of the SARA score (Diallo et  
64 al., 2020). In addition, the responsiveness to change of the SARA has already been studied in several ataxias  
65 (Traschütz et al., 2023) where some modifications of the scale by removing items seemed to increase its overall  
66 responsiveness. However, the course of individual items and their contribution to the overall scale in terms of  
67 responsiveness to change has not been investigated in SCA1, 2, 3, and 6.

68 In this study, we aim to (1) assess the progression of the total score and of each item and their differences  
69 between cohorts and SCAs, (2) describe the contribution of each item to the total scale across all SARA ranges,  
70 (3) analyze the responsiveness to change of the total scale by sample size estimates, and find potentially better  
71 items combinations to create a more responsive scale.

72 For the purpose of our study, we pooled data of SCA1, 2, 3, and 6 patients from four cohorts (EUROSCA, CRC-  
73 SCA, SPATAX, and RISCA cohorts). The first three are composed of ataxic patients and RISCA only included  
74 pre-ataxic participants, allowing us to have patients at all stages of the disease.

75

## 76 **MATERIALS AND METHODS**

### 77 *Study population*

78 Data from the four cohorts of SCA carriers were pooled together. Three cohorts included affected subjects with 2  
79 European cohorts: EUROSCA (Jacobi et al., 2015) and SPATAX (Monin et al., 2015)) and one from the USA:  
80 CRC-SCA (Ashizawa et al., 2013). The fourth cohort (RISCA) included European pre-symptomatic expansion  
81 carriers (Jacobi et al., 2020). From these cohorts, which included participants with different SCA types, we have  
82 selected the subjects with a positive genetic test for *ATXN1*, *ATXN2*, *ATXN3*, or *CANCA1A* gene. Only patients  
83 with at least 2 visits with available information on SARA and SARA items were kept for analysis. The  
84 characteristics of the four cohorts are given below and in Table 1.

85 **EUROSCA:** The study was conducted in 17 European centers. Patients were eligible if they had progressive,  
86 otherwise unexplained ataxia and a positive molecular genetic test for SCA1, SCA2, SCA3, or SCA6. Patients  
87 were consecutively recruited within a predetermined time frame between July 2005 and August 2006. Patients  
88 were seen at a baseline visit, followed by annual visits for 3 years. After the initial 3-year observation period,

89 study participants entered an extension phase in which study assessments were performed in conjunction with  
90 routine visits resulting in irregular intervals between visits.

91 **CRC-SCA:** The study was conducted at 12 U.S. centers. Patients were eligible if they had a positive molecular  
92 genetic test for SCA1, SCA2, SCA3, and SCA6 and if they were at least 6 years of age. Subjects with  
93 comorbidities affecting SARA and other ataxia measures used in the study were excluded. The study began in  
94 April 2010. Clinical assessments were performed at the baseline visit and every six months until two years from  
95 the baseline visit or until the end of August 2012. The study continued after August 2012, but we only had data  
96 from the first 2 years.

97 **RISCA:** Between September 13, 2008, and December 1, 2011, offspring or siblings of patients with SCA1,  
98 SCA2, SCA3, or SCA6 were enrolled in a prospective, longitudinal observational study at 14 European centers.  
99 To be eligible for inclusion in this study, individuals had to have no ataxia and between the ages of 18–50 years  
100 if directly related to individuals with SCA1, SCA2, or SCA3, or between the ages of 35–70 years if directly  
101 related to individuals with SCA6. Non-converters, i.e. patients without a visit with a SARA > 3 were removed  
102 from the database. These patients have irregular visits but some of them are seen by the clinician on an annual  
103 basis.

104 **SPATAX:** Since 2005 (first visit with SARA assessed), all individuals with spinocerebellar degenerations were  
105 referred to the National (French) reference center for neurogenetic diseases and were entered into the SPATAX  
106 database (created in 2000, using the REDCap electronic data capture tools for data collection and management),  
107 which was hosted and insured by the Paris Brain Institute (Institut du Cerveau, ICM). We included patients with  
108 SCA 1, 2, 3, and 6. We removed the overlapping individuals from EUROSCA and RISCA because SPATAX  
109 participated in these studies.

110

### 111 **Outcomes**

112 To assess the cerebellar ataxia, we used the SARA score (Schmitz-Hubsch et al., 2006). In addition, we analyzed  
113 the SARA items, grouped as follows: the four axial SARA items (*gait* (0-8), *stance* (0-6), *sitting* (0-4) and  
114 *speech disturbance* (0-6)) and the four appendicular SARA items (*finger-chase* (0-4), *nose-finger* (0-4), *fast-*  
115 *alternating hand movements* (0-4), and *heel-shin slide* (0-4)). Appendicular items are calculated as the average of  
116 both sides, resulting in half-point values. Participants were stratified into three groups according to their SARA  
117 at baseline: Early-stage patients (<10), intermediate-stage stage (10-25), and advanced stage (>25). These  
118 thresholds are arbitrary but were chosen to detect potential non-linear effects of the baseline SARA.

119 Age of onset is defined as the patient-reported time of disease onset. For RISCA participants who converted  
120 during the study, the age at onset was not reported and was taken to be the age at the first visit with a SARA  
121 greater than 3. The estimated age at onset was calculated using the CAG repeats as proposed for SCA1, 2, and 6  
122 (Tezenas du Montcel et al., 2014) and for SCA3 (Peng et al., 2021). The Time to Onset (TTO) was defined as  
123 the time to the estimated age at onset at a given time.

124

125 ***Statistical analysis***

126 Descriptive statistics

127 Baseline data are described using frequencies and percentages for qualitative data and means and standard  
128 deviations (SD) for quantitative variables. To compare the sample selected for analysis (at least two visits) with  
129 participants not selected for analysis (no follow-up) and to compare the characteristics of the patients in each  
130 cohort we used a chi-squared test for qualitative variables and ANOVA for quantitative variables.

131

132 Modeling of the SARA score progression

133 We modeled the change from baseline in the full SARA score and the eight SARA items. We used linear mixed  
134 models estimated by maximum likelihood. We first tested cubic, quadratic, and linear progressions to detect  
135 potential floor or ceiling effects. The significance of the cubic and quadratic effects was assessed using the  
136 likelihood ratio test. Because we were examining the change from baseline, no fixed intercepts were included in  
137 the model, only fixed slopes. The random effect included the individual's intercept and slope.

138 For full SARA models, the effect of the cohort, stage group (early, intermediate, and advanced stage), and  
139 normalized expanded CAG repeat length was assessed by adding interaction with the slope for these covariables.  
140 Non-significant covariables with the lowest mean sum of squares were iteratively removed from the model.  
141 CAG repeat length was standardized within all SCAs and the effect of CAG on the slope was expressed as the  
142 annual point of SARA per standard deviation of CAG repeat length. For item-level models, we adjusted all  
143 models for cohort, stage group, and CAG repeat length.

144

145 Transversal Item contribution to the full-scale

146 Each SARA item was divided by its maximum score, normalizing them between 0 and 1 to make them  
147 comparable. For this analysis, the SARA score was divided into increments of 5 between 0 and 40 and, within  
148 each division, the mean and the 95% CI interval for each item were calculated, allowing us to compare the  
149 relative contribution of each item to the full scale. The mean value was also compared to a theoretical  $x=y$   
150 straight line representing what an equal contribution of the items to the scale would look like.

151

152 Sample size calculation

153 To estimate the sensitivity of SARA and items combination, we simulated data at 1 year after inclusion and  
154 calculated the mean and SD of the variation. Data were simulated after determining whether the progression  
155 included quadratic and cubic effects. We then calculated the sample size needed to detect a 50% reduction in  
156 progression with 80% power. In each subset by SCA or by cohort, we iteratively added items that most increased  
157 (or less decreased) the sample size to build a *stepwise-optimized SARA* (SO-SARA), inspired by (Traschütz et  
158 al., 2023).

159 Statistical tests were performed at the conventional two-tailed type I error of 0.05. Data were analyzed using R  
160 version 4.2.0 (R Core Team, 2018).

161

162 **RESULTS**

163 ***Data description***

164 Patients with only 1 visit, who were not included in the further analysis, had higher SARA at baseline and longer  
165 disease duration (Supplementary Table 1), suggesting a lower probability of follow-up when at more advanced  
166 disease stages. A total of 850 mutation carriers were included in the analysis: 186 SCA1 (107 EUROSCA, 37 in  
167 CRC-SCA, 16 in SPATAX, and 26 in RISCA), 248 SCA2 (146 EUROSCA, 51 CRC-SCA, 29 SPATAX, and 22  
168 RISCA), 272 SCA3 (120 EUROSCA, 91 CRC-SCA, 50 SPATAX, and 11 RISCA) and 144 SCA6 (86  
169 EUROSCA, 52 CRC-SCA, 4 SPATAX, and 2 RISCA), for a total of 3431 observations. The median number of  
170 visits per patient was 4 (3, 5) and the mean time between two visits was  $14.1 \pm 8.7$  months. These figures were  
171 heterogeneous between the cohorts: SPATAX participants had the lowest mean number of visits ( $2.9 \pm 1.1$ ) and  
172 EUROSCA ones the highest ( $4.8 \pm 1.7$ ). CRC-SCA had the shortest time between two visits ( $6.6 \pm 1.6$  months) and  
173 RISCA had the longest ( $25.8 \pm 8.5$  months).

174 The cohorts differed in the following characteristics (Supplementary Table 2, 3, 4, and 5): RISCA subjects were  
175 younger than the other three cohorts due to their inclusion criteria (SARA <3 at the baseline visit). In SCA1 and  
176 SCA3, there were significant differences in CAG repeat length between the cohorts. In SCA1, CRC-SCA  
177 participants had significantly fewer CAG repeats than SPATAX and EUROSCA participants ( $46.0 \pm 3.6$  vs  
178  $47.7 \pm 5.7$  and  $50.3 \pm 6.8$ ,  $p=0.021$  and  $p=0.028$  respectively) and later age of onset. In SCA3, CRC-SCA  
179 participants had longer CAG repeat lengths than EUROSCA ones ( $70.4 \pm 3.6$  vs  $68.8 \pm 4.2$ ,  $p=0.0037$ ), but this was  
180 not associated with a difference in ages of onset.

181 Among the cohorts with ataxic patients at baseline, CRC-SCA participants had lower SARA at baseline than  
182 SPATAX participants in SCA2 and SCA3 ( $p=0.017$  and  $p=0.038$  respectively).

183

#### 184 ***Modeling of the SARA score progression from baseline***

185 The models of progression from baseline are described in Table 2. All models included quadratic or cubic  
186 effects. The cohort interaction with slope was significant for SCA1 ( $p=0.001$ ), SCA2 ( $p=0.0007$ ), and SCA3  
187 ( $p<0.0001$ ). EUROSCA participants always had the higher linear component with  $2.19 \pm 0.13$ ,  $1.69 \pm 0.11$ , and  
188  $1.52 \pm 0.12$  in SCA1, SCA2, and SCA3, respectively. RISCA subjects had the slowest progression in SCA1  
189 ( $1.32 \pm 0.21$ ), SPATAX subjects in SCA2 ( $0.84 \pm 0.23$ ), and CRC subjects in SCA3 ( $0.68 \pm 0.18$ ). The effect of  
190 CAG repeat length on the slope was significant for SCA1 ( $0.36 \pm 0.09$ ,  $p < 0.0001$ ) and SCA2 ( $0.27 \pm 0.07$ ,  $p =$   
191  $0.0002$ ), after adjustment for the cohort. Patients in the advanced stage had a slower progression in SCA2 and  
192 SCA6, with a reduction in the linear progression of  $-1.05 \pm 0.24$  and  $-0.90 \pm 0.33$ , respectively, compared to  
193 patients at an intermediate stage.

194

#### 195 ***Items contribution to the total score***

196 Throughout the progression of the total SARA, the contribution of the items was variable depending on the  
197 disease stage and the SCA (Figure 1). The *sitting* item had a low contribution in the early and intermediate stages  
198 in each SCA as its mean normalized value was lower than any other item in each group with SARA < 20. In  
199 SCA1 and SCA2, items *gait*, *stance*, *hand-movement*, and *heel-shin* had higher mean normalized scores than  
200 *finger-chase* and *nose-finger* for groups with SARA between 15 and 30. In SCA2 specifically, *heel-shin* had a  
201 significantly higher value than any other item in the 0-5 SARA visit group. In SCA3, the differences in dynamics  
202 between items were larger: *gait* was significantly higher than any other item in visit groups with SARA from 15  
203 to 30.

204

### 205 ***Modeling of the item progression from baseline***

206 The effect of cohort, CAG repeat length, and SARA at baseline on item progressions were very heterogeneous  
207 among SCAs (Figure 2). The cohort effect was significant for *gait* in SCA1, SCA2, and SCA3, with EUROSCA  
208 having the fastest progression, followed by CRC-SCA. SCA3 had the strongest cohort effect, significant for all  
209 items except *sitting* and *speech*, and CRC-SCA patients had the slowest progression, for all appendicular items  
210 with a significant improvement for the *nose-finger* item). CAG repeat length had a significant effect only in  
211 SCA1 and SCA2, for all items but *speech* and *sitting*. For all SCAs, advanced stage patients had slower  
212 progression in *gait* and *stance* compared to early and intermediate stages.

213

### 214 ***Stepwise Optimized SARA by SARA at baseline***

215 For intermediate and early-stage patients, the sample size required to assess a 50% reduction in total SARA  
216 progression over one year was 120 and 126, respectively (Figure 3A). The best sensitivity of the SO-SARA was  
217 achieved with five items representing a sample size reduction of 4% and 10% in early and intermediate-stage  
218 patients, respectively, compared to the full SARA (n=115 and n=113). In the advanced-stage patients, the best  
219 sample size was also achieved with five items, but increased significantly with additional items, resulting in a  
220 sample size reduction of 47% compared to full SARA. In the next analysis, we decided to remove advanced  
221 patients due to their differences in progression compared to early and intermediate.

### 222 ***Stepwise Optimized-SARA by SCA***

223 The sample size required to detect a 50% reduction in SARA progression over 1 year in the pooled cohort was  
224 the lowest in SCA1 (n=81) due to faster progression (Figure 3B). The total SARA was never the most sensitive  
225 scale in any SCA. The best sensitivity was achieved with three, six, four, and two items for SCA1, SCA2, SCA3,  
226 and SCA6, respectively. Compared to total SARA, it reduces the sample size by 24 (30%), 3(3%), 39 (26%) and  
227 265 (55%) respectively. *Gait* was the best item overall, ranked 1<sup>st</sup> in all SCAs except SCA1. *Speech* and *hand-*  
228 *movements* were well ranked, and always improved the sensitivity of the SO-SARA (except *Hand-movements* in  
229 SCA1). In the total dataset, i.e. with all SCAs pooled, the best sensitivity was achieved with 4 items (*Gait*,  
230 *stance*, *Speech* and *Hand-movements* included), but this reduced the sample size by only 8 (6%) patients  
231 compared to the full scale.

### 232 ***Stepwise Optimized SARA by cohort***

233 The sample size required to detect a 50% reduction in full SARA progression over 1 year was the highest with  
234 the progression estimation from the CRC-SCA cohort (n=273) and the lowest with the progression estimation  
235 from the EUROSCA cohort (n=108) (Figure 3C). The most sensitive items were heterogeneous between cohorts,  
236 but *gait* was the most sensitive in all cohorts except SPATAX (ranked 3<sup>rd</sup>), where the best item was *speech*.

237

238

## 239 **DISCUSSION**

240 In this retrospective multi-cohort analysis, we have shown that there are large discrepancies in SARA  
241 progression between cohorts and SCAs at both the full scale and the item level. Analysis of sensitivity to change  
242 of various combination of items highlighted that no item removal can reliably increase the sensitivity of the scale  
243 in every SCAs or population.

244 A total of 850 patients with ataxia or close to ataxia onset with pathologic repeats in ATXN1, ATXN2, ATXN3,  
245 and CACNA1A were analyzed for ataxia progression over 3431 visits with a mean follow-up of  $4.15 \pm 2.98$  years.  
246 At baseline, apart from the obvious differences in the RISCA participants compared to the ataxia cohorts, there  
247 were only slight differences in CAG repeat length in the SCA1 and SCA3 cohorts, with CRC-SCA patients  
248 having shorter repeats than EUROSCA patients. Ataxia progression from baseline was assessed as the change in  
249 SARA score. We found that the progression from baseline had a slight ceiling effect (except for SCA6, where  
250 the quadratic effect was positive), but was almost linear in the early stages. This ceiling effect could be  
251 explained by the slower progression observed in the advanced stage patients, but also by slower progression in  
252 patients with longer follow-up (Jacobi et al., 2015). The early and intermediate stage patients showed no  
253 differences in progression, suggesting that SARA increases steadily after it exceeds 3. In ataxic patients and  
254 converters, the pace of SARA progression since enrollment was consistent with previous findings, with linear  
255 component progression in cohorts ranging from 1.32-2.19, 0.84-1.69, 0.68-1.52, and 0.8 for SCA1, 2, 3, and 6,  
256 respectively (Jacobi et al., 2011, p. 6). Large differences in the rate of SARA progression between cohorts were  
257 noted for SCA1, SCA2 and SCA3 patients, with EUROSCA participants progressing faster than any other  
258 cohort. These differences were also present at the item level and cannot be explained by geographic or ethnic  
259 reasons, as SPATAX participants (French cohort) had a progression more similar to CRC-SCA participants (US  
260 cohort) than EUROSCA participants (European cohort). These differences cannot be explained by disease stage  
261 or genetic factors as they were similar between cohorts. One bias could be that SPATAX contributed to  
262 EUROSCA and RISCA, and thus the remaining SCA patients in SPATAX have a different profile than the  
263 inclusion criteria of EUROSCA/RISCA. Also, there were no SARA training tool available at the time of the data  
264 collection, but EUROSCA raters were the ones involved in development of the scale, resulting in higher  
265 experience in the use of the scale compared to other cohorts. In addition, the follow-up time of the SPATAX or  
266 CRC-SCA cohort was shorter than that of the EUROSCA cohort, which may lead to a higher misestimating of  
267 SARA progression.

268 In the analysis of the contribution of each item to the SARA scale, the contribution of the items to the total scale  
269 was heterogeneous throughout disease progression, with *gait*, *stance*, and *heel-shin* having higher contribution in  
270 the early stage and *sitting*, *finger-chase*, and *nose-finger* in the later stage. In addition, the progression of the  
271 items was heterogeneous; *gait* and *stance* (respectively ranging from 0-8 and 0-6) items were progressing faster,  
272 as would be expected with their wider range. The *speech* item showed moderate progression despite ranging  
273 from 0-6. Similar to previous report (Jacobi et al., 2011), the expanded CAG repeat length was associated with  
274 faster SARA progression in SCA1 and SCA2, and even at the item level.

275 In the context of a clinical trial using SARA as the primary endpoint, SCA1 patients would require a smaller  
276 sample size due to faster progression, with 81 patients required for a 1-year trial with a 50% efficacy of the  
277 intervention tested. The SO-SARA analysis showed that a few items mainly drive the sensitivity to change of  
278 SARA, and the addition of less sensitive items leads to a very small decrease (or even increase) of the sample  
279 size. However, even though the axial items were often the most sensitive ones, the sensitivity ranking of items  
280 was heterogeneous among SCAs and cohorts. This shows that even if total SARA was never the best  
281 combination of items in terms of sensitivity, there is no combination of items that would improve the  
282 responsiveness in all SCAs or populations taken separately. In addition, the differences between cohorts



283 highlight that these conclusions are highly dependent on the data used and that the absolute value of sample size  
284 estimate must be taken with caution.

285 The estimated sample sizes remain very large for such a rare disease as our estimations are based on a 1-year  
286 trial and with a 50% reduction on the slope, namely a relatively strong treatment effect. Moreover, one limitation  
287 in our analysis is that we did not consider any placebo effect, assuming that the placebo arm would progress  
288 similarly to the natural history, which is unlikely (Choi et al., 2022; Coarelli et al., 2022).

289 Although SARA remains a good tool for assessing the ataxia severity, the relatively slow progression of the  
290 patients with SCA diseases limits the relevance of using a clinical scale to show moderate treatment effects in  
291 short-term clinical trials. This is very clear in SCA6, the slowest progressing SCA, where the best combination  
292 of items reduced by 55% the sample size required compared to full SARA. Clinical trials should focus on  
293 detecting changes in biomarkers levels, especially in the pre-ataxic stage which has been shown to be a relevant  
294 time window for treating patients. Modification of biomarkers modifications (NFLs (Faber et al., 2023; Tezenas  
295 Du Montcel et al., 2023), MRI (Chandrasekaran et al., 2022)) already occurs at this stage while the SARA  
296 remains at very low levels. The READISCA project (for which longitudinal data will soon be available), which  
297 includes both pre-ataxic and ataxic SCA1 and SCA3 participants in a multi-continental study, will help to clarify  
298 these early changes.

299

## 300 **DECLARATIONS**

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## 314 **References**

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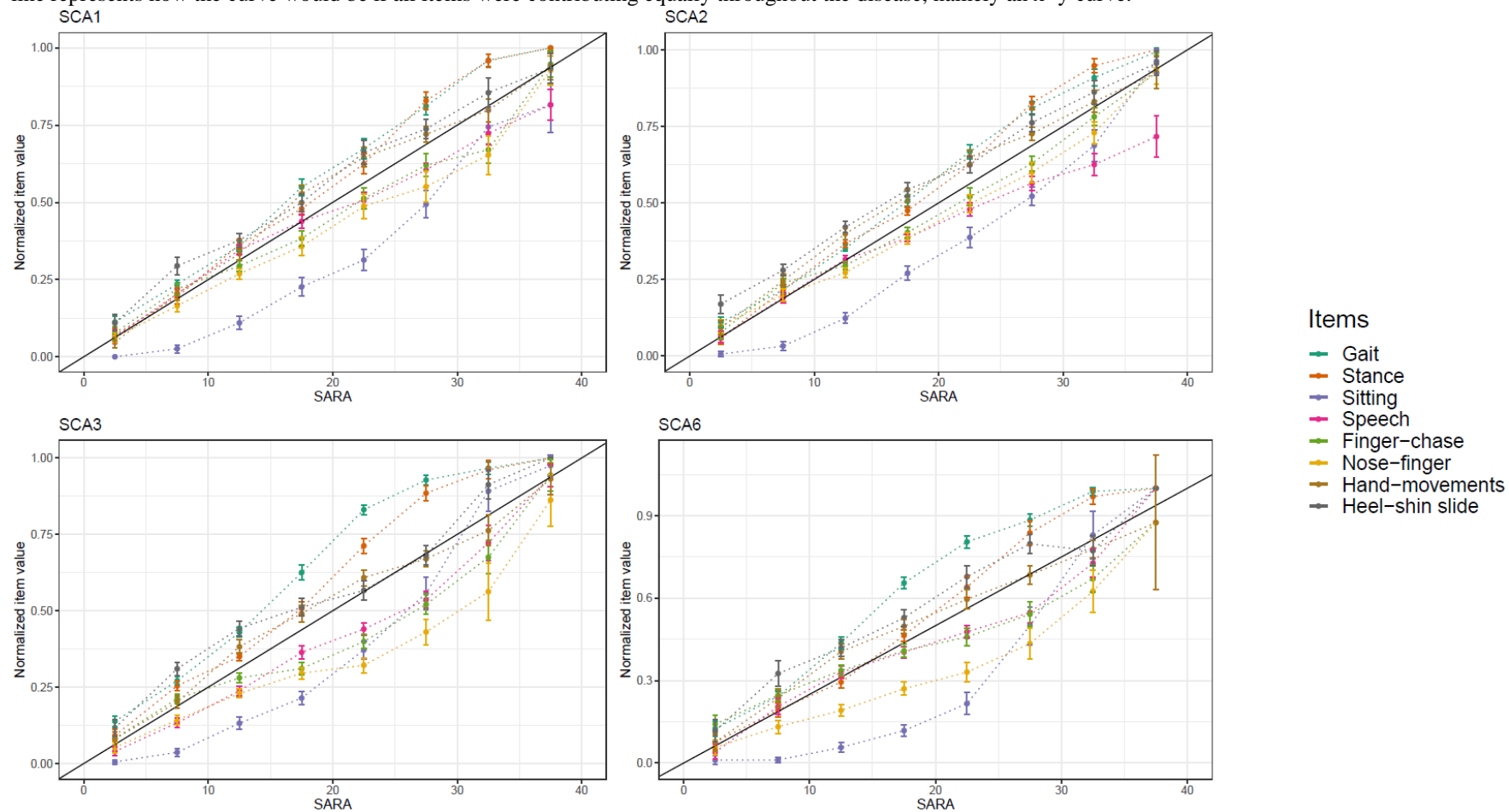
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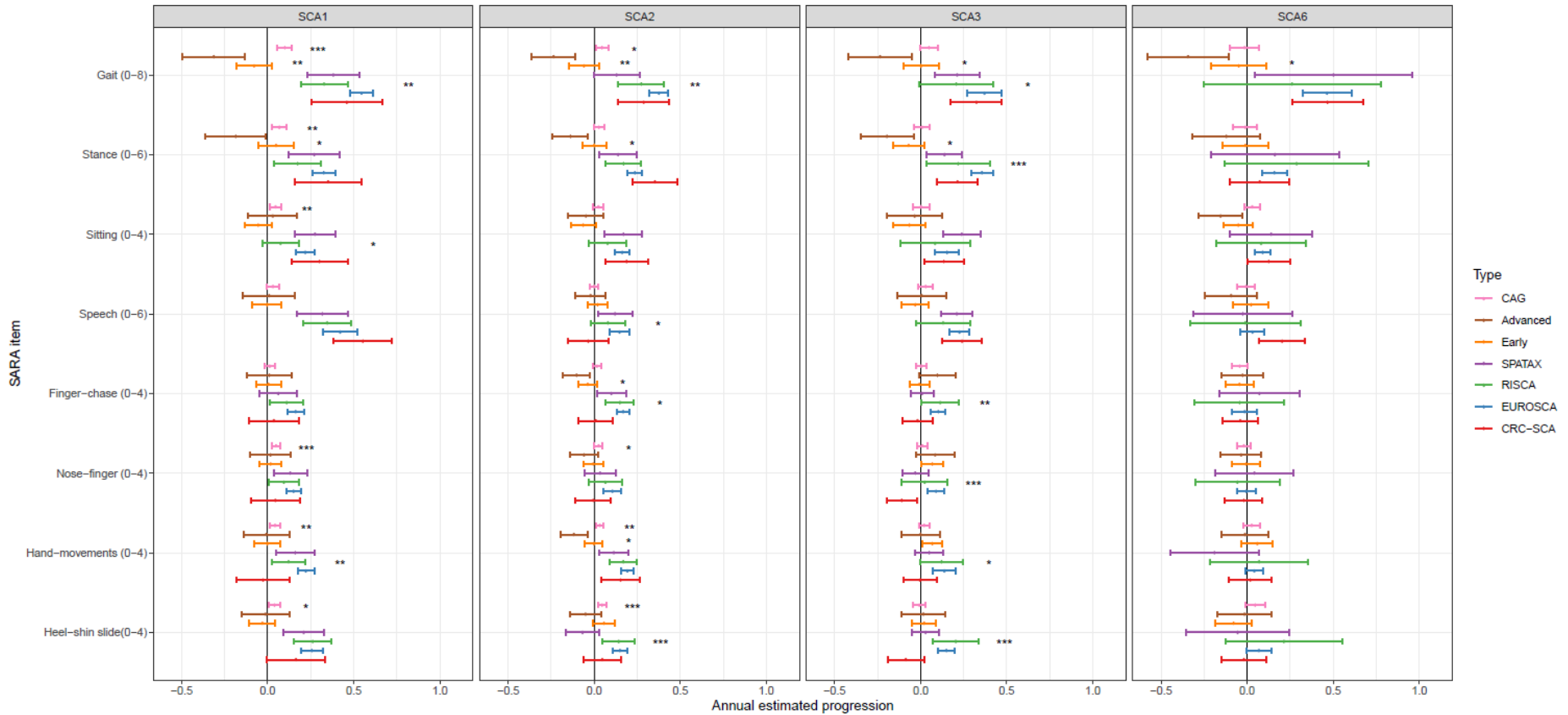
**Figure 1: Contribution to the SARA scale of each individual item of the scale**

Each point represents the average (with 95% CI) of a normalized item score for a group of visits in increments of 5 SARA points. For each class, the point is displayed in the middle of the class: for instance, the point referring to the 0-5 SARA group is displayed at SARA = 2.5. Non-overlapping CI are considered significant differences. The black line represents how the curve would be if all items were contributing equally throughout the disease, namely an  $x=y$  curve.



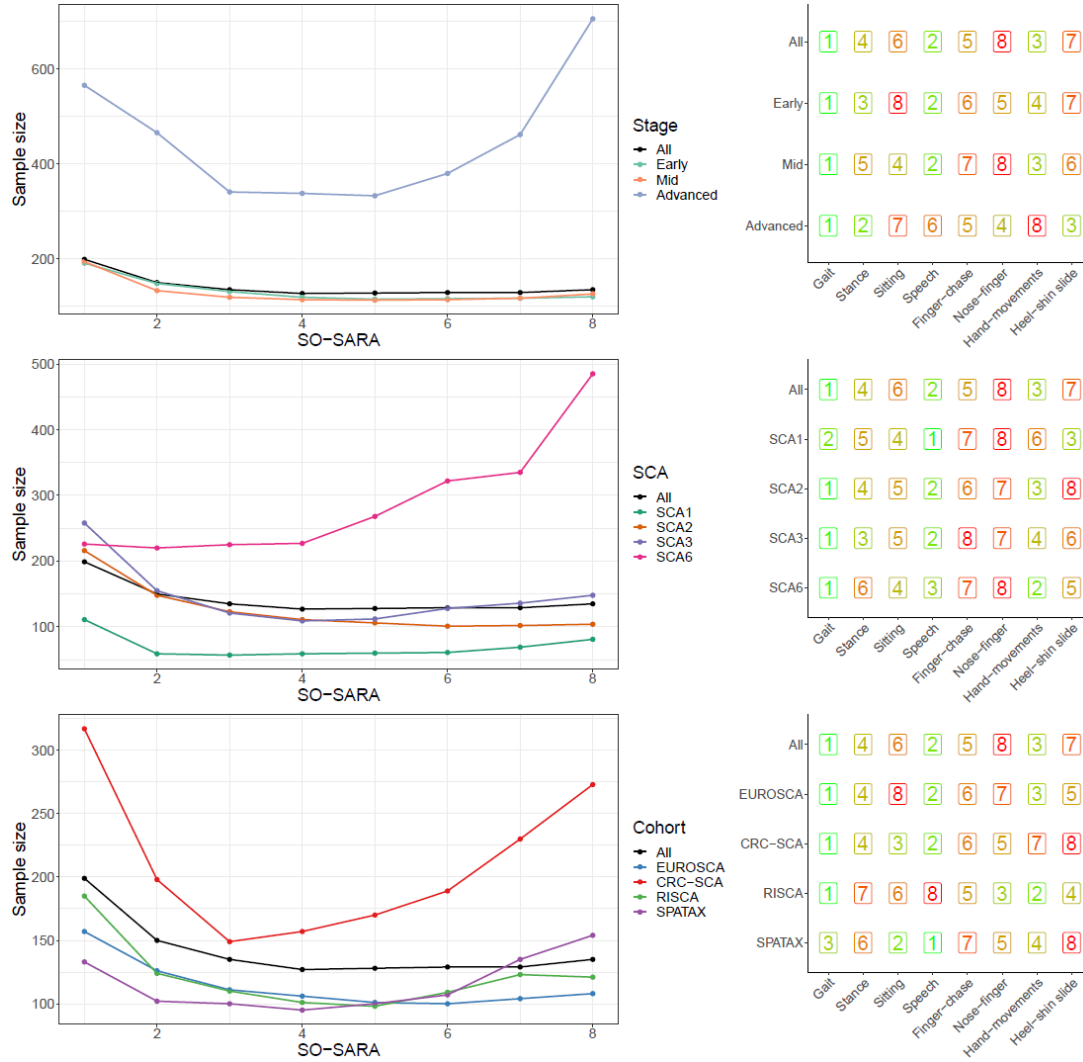
**Figure 2: Cohort, stage and CAG effect on item progression**

The estimations (with 95% CI) of the interaction between the covariables and time in the linear mixed effect model are displayed. Quadratic and cubic effects were tested for all items, but not shown in this graph if significant as their effects are negligible in early years. Significance of effects are represented as \*\*\* if p-value < 0.001, \*\* if p-value < 0.01 and \* if p-value < 0.05. For cohort effects, the p-value indicates that it exists a significant difference of the linear progression between cohorts. For CAG, the p-value indicates that the CAG effect is significantly different from 0. For stage groups, the p-value indicates that at least one group is progressing faster or slower than the reference group (Intermediate group).



**Figure 3: Stepwise-optimized SARA by stage, SCA and cohort**

The left panels show the sample size estimation for each SO-SARA created. The right panels show in which order the items were added to the SO-SARAS to ensure maximum increase (or minimum decrease) of sensitivity to change.



**Table 1: Cohort's Inclusion criteria and follow-up characteristics**

	<b>CRC-SCA</b>	<b>EUROSCA</b>	<b>RISCA</b>	<b>SPATAx</b>
Study Population	Patients with SCA 1, 2, 3 and 6 of all races/ethnicities and both genders	Patients with SCA 1, 2, 3 and 6	Unaffected adults' individuals that descend from SCA1, SCA2, SCA3 and SCA6 patients	Patients with SCA 1, 2, 3 and 6
Inclusion Criteria				
Ataxia	Presence of symptomatic ataxic disease	Progressive, otherwise unexplained ataxia	Absence of ataxia (SARA < 3)	
Molecular diagnosis	Pathogenic expansions in ATXN1, 2, 3 and CACNA1A either in the subject or another affected family member	Pathogenic expansions in ATXN1, 2, 3 and CACNA1A	Offspring and sibs of an individual with a pathogenic expansion in ATXN1, 2, 3 and CACNA1A	Pathogenic expansions in ATXN1, 2, 3 and CACNA1A
Age	6 years and above.	-	- 18 - 50 years for descendants of SCA1, SCA2 or SC3 patients - 35 - 70 years for descendants of SCA6 patients	>18 years

Consent	Willingness to participate in the study and ability to give informed consent	Written informed consent by the patient or his legal agent	Written, informed consent	Written, informed consent
Number of visits	3.0±1.2	4.8±1.7	4.0±1.0	2.9±1.1
Time between 2 visits (months)	6.6± 1.6	14.3 ± 6.8	25.9 ± 8.5	19.5 ± 15.4
Follow-up time (years)	1.1±0.5	4.5±2.4	6.5±2.0	3.1±2.0



**Table 2: Models of SARA progression since inclusion**

	SCA1			SCA2			SCA3			SCA6		
Predictors	Estimates	SE	p-value	Estimates	SE	p-value	Estimates	SE	p-value	Estimates	SE	p-value
Cohort effect			<b>0.001</b>			<b>0.0007</b>			<b>&lt;0.0001</b>			
[CRC] * TIME	1.75	0.33	<b>&lt;0.0001</b>	1.08	0.22	<b>&lt;0.0001</b>	0.68	0.18	<b>0.0001</b>			
[EUROSCA]* TIME	2.19	0.13	<b>&lt;0.0001</b>	1.69	0.11	<b>&lt;0.0001</b>	1.52	0.12	<b>0.0001</b>			
[RISCA] * TIME	1.32	0.21	<b>&lt;0.0001</b>	1.31	0.27	<b>&lt;0.0001</b>	1.11	0.30	<b>0.0002</b>			
[SPATAX] * TIME	1.60	0.30	<b>&lt;0.0001</b>	0.84	0.23	<b>0.0004</b>	0.81	0.18	<b>&lt;0.0001</b>			
TIME										0.80	0.14	<b>&lt;0.0001</b>
TIME^2	-0.026	0.016	0.10	-0.037	0.007	<b>&lt;0.0001</b>	0.028	0.030	0.35	0.039	0.014	<b>0.0056</b>
TIME^3							-0.004	0.002	<b>0.03</b>			
Stage group effect						<b>&lt;0.0001</b>						<b>0.028</b>
[EARLY] * TIME				-0.09	0.17	0.60				-0.19	0.22	0.39
[ADVANCED] * TIME				-1.05	0.24	<b>&lt;0.0001</b>				-0.90	0.33	<b>0.008</b>
[CAG] * TIME	0.36	0.09	<b>&lt;0.0001</b>	0.27	0.07	<b>0.0002</b>						

Models were selected by first determining the presence of a quadratic or cubic effect. Covariate effects were then tested, and nonsignificant covariates with the smallest sum of squares were iteratively removed. For the stage group effect, intermediate participants were used as the reference. \*: If there is a significant cohort effect, the linear term is reported for each of the respective cohorts ([cohort]\*TIME).