Capturing the fragile X premutation phenotypes: a collaborative effort across multiple cohorts

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Abstract

Objective—To capture the neuropsychological profile among male carriers of the FMR1 premutation allele (55-200 CGG repeats) who do not meet diagnostic criteria for the late-onset fragile X-associated tremor/ataxia syndrome, FXTAS.

Method—We have initiated a multi-center collaboration that includes three independent cohorts totaling 100 carriers of the premutation and 216 non-carriers. The initial focus of this collaboration has been on executive function. Four executive function scores are shared among the three cohorts (Controlled Oral Word Association Test, Stroop Color-Word Test, and Wechsler backward digit span and letter-number sequencing) while additional executive function scores are available for specific cohorts (Behavior Dyscontrol Scale, Hayling Sentence Completion Test Part B, and Wisconsin Card Sorting Test). Raw scores were analyzed using statistical models that adjust for cohort-specific effects as well as age and education.

Results—Carriers scored significantly lower compared to non-carriers on the Stroop Color-Word Test (p=0.01), Hayling Sentence Completion Test Part B (p<0.01), and Behavioral Dyscontrol Scale (p=0.03), with the Hayling displaying a significant age-related decline (p=0.01), as assessed by an age and repeat length group interaction. Follow-up analysis of the collective data did not identify any specific age groups or repeat length ranges (i.e. low premutation=55-70 repeats, mid premutation=71-100 repeats, high premutation=101-199 repeats) that were associated with an increased risk of executive function deficits.

Conclusions—Preliminary analyses do not indicate global executive function impairment among male carriers without FXTAS compared to non-carriers. However, impairment in inhibitory capacity may be present among a sub-set of carriers, though the risk factors for this group do not appear to be related to age or repeat length.

Keywords

FMR1; premutation; CGG repeat; executive function; FXTAS
INTRODUCTION

The X-linked fragile X mental retardation 1 gene (FMR1) is associated with a group of disorders referred to as fragile X-associated disorders. FMR1 contains a polymorphic CGG trinucleotide repeat sequence in the 5’ untranslated region of the gene, which can become unstable and expand from one generation to the next. Normal CGG repeat sizes are between 6 and 54 repeats, with 29 or 30 repeats as the most common (Y. H. Fu et al., 1991). An expansion greater than 200 repeats, termed a full mutation, generally results in hypermethylation and transcriptional silencing of the FMR1 locus (Feng et al., 1995; Sutcliffe et al., 1992; Verkerk et al., 1991). The subsequent absence of the fragile X mental retardation protein (FMRP) is associated with fragile X syndrome (Pieretti et al., 1991). FMRP is specifically involved in synapse formation, maturation and function, and its absence results in the characteristic intellectual impairment and behavioral profile associated with fragile X syndrome (Till, 2010). Autistic features are present among a proportion of individuals with fragile X syndrome (Hatton et al., 2006); thus, the FMR1 full mutation represents one of the few known single-gene causes of autism spectrum disorder (K. Cornish et al., 2008).

An expansion between 55 and 199 repeats, termed a premutation, is capable of expanding to a full mutation in a single generation when passed from mother to offspring, and thus is considered “carrier” status for fragile X syndrome (S. D. Fu et al., 1994; Oberle et al., 1991). The premutation is relatively common in the general population, found in about 1/100 to 1/250 females (Cronister et al., 2008; Toledano-Alhadef et al., 2001) and in about 1/250 to 1/800 males (Dombrowski et al., 2002; Fernandez-Carvajal et al., 2009) in a predominantly Caucasian sample. At the molecular level, individuals harboring premutation alleles, unlike those with the full mutation, produce 2-fold to 10-fold increased levels of FMR1 mRNA, but reduced levels of FMRP (Allen et al., 2004; Kenneson et al., 2001; Peprah et al., 2010; Primerano et al., 2002; Tassone, Hagerman, Taylor, Gane, et al., 2000; Tassone, Hagerman, Taylor, Mills, et al., 2000).

In the last decade, the phenotype of carriers of the premutation has received considerable attention, spurred by the identification of a fragile X premutation-associated neurodegenerative disorder, fragile X-associated tremor/ataxia syndrome (FXTAS). This disorder, which occurs in approximately 40% of premutation males (> 50 years) and less than 10% of females (Coffey et al., 2008; Jacquemont et al., 2004), is characterized by a constellation of symptoms that include progressive gait ataxia and action tremor (Hagerman et al., 2001; Leehey et al., 2003), parkinsonism (Jacquemont et al., 2003), and executive dysfunction, notably affecting inhibitory control and working memory (Grigsby et al., 2008; Grigsby et al., 2007). Neuroradiologic abnormalities in FXTAS patients include generalized atrophy and white matter disease as well as a distinctive hyperintensity of the middle cerebellar peduncles on T-2 magnetic resonance imaging that is considered a diagnostic hallmark of FXTAS (Brunberg et al., 2002; S. Cohen et al., 2006). Neuropathologic changes include atrophy, spongiform changes in the middle cerebellar peduncles, Purkinje cell loss in the cerebellum, and characteristic neuronal intranuclear inclusions (Greco et al., 2002). Penetration of FXTAS among premutation carriers is a function of age and repeat length, with roughly 30% of carriers over age 50 developing FXTAS and most carriers with FXTAS having greater than 70 repeats (Jacquemont, et al., 2004; Jacquemont et al., 2006).

To date, the cognitive profile of premutation carriers without FXTAS has remained unclear (Hunter et al., 2009). However, recent fMRI data indicate changes in prefrontal activity in premutation carriers, irrespective of FXTAS diagnosis, during performance of a working memory task (Hashimoto et al., 2010). These preliminary findings provide the first evidence...
to suggest vulnerability of specific brain regions associated with neural networks mediating executive cognitive functioning among persons in the premutation range, irrespective of a diagnosis of FXTAS. In addition, accumulating findings indicate that among men with FXTAS, larger CGG repeat is associated with greater ataxia and action tremor (Leehey et al., 2008) and poorer executive function (Brega et al., 2008; K. M. Cornish et al., 2008). Therefore, it is of considerable clinical interest to determine whether there exists an age-related subpopulation with executive function impairments that can be identified among premutation carriers, perhaps prior to the onset of FXTAS. To date, individual studies have produced mixed results and all have been limited by relatively small samples sizes with variability in age range and CGG repeat distribution across studies (e.g., Grigsby et al., 2008, Cornish et al., 2008, Hunter et al., 2008).

In the present study, we analyzed data from a multi-center collaboration that included three independent cohorts totaling 100 carriers of the premutation and 216 non-carriers. The primary goal of this collaboration was to determine whether a profile of executive function deficits emerged among premutation carriers asymptomatic for FXTAS when analyzed in the largest sample to date, and, if present, whether these deficits emerged as a function of age or repeat length.

**METHODS**

**Subjects**

Subjects included in this collaboration were recruited as part of three independent studies initiated to assess neuropsychological phenotypes associated with *FMR1* premutation alleles. Though analyses from these independent cohorts have been previously published (Brega, et al., 2008; Cornish, et al., 2008; Grigsby, et al., 2008; Hunter et al., 2008), we have combined these cohorts for a large-scale analysis of executive function. Cohort information, including recruitment, is reported in Table 1.

**FMR1 Genotyping**

Biological samples were obtained from subjects within each cohort for molecular analysis of the *FMR1* CGG repeat length using methods previously published (cohort 1: Cornish et al., 2008, cohort 2: Hunter et al., 2008, cohort 3: Brega et al., 2008 and Grigsby et al., 2008). Briefly, cohort 1 was genotyped using a direct PCR method modified from Wang et al. (1995) and Southern Blot (Knight et al., 1993), cohort 2 was genotyped using a fluorescent-sequence method (Meadows et al., 1996) and a second PCR-based hybridization method when necessary to detect high-repeat alleles (Brown et al., 1993), and cohort 3 was genotyped with a PCR-based assay and Southern Blot.

**Measurement of Executive Function**

Since each cohort included in this collaboration came from an independently initiated study to assess neuropsychological profiles among adult male premutation carriers, test batteries were variable across cohorts. However, we were able to identify four measures of executive function shared across all three cohorts: Controlled Oral Word Association Test, Stroop Color and Word Test, and the Wechsler measures of backward digit span and letter-number sequencing. In order to expand the assessment of the executive function profile beyond the four measures above, we also identified one measure unique to each cohort to be included in the analyses: the Hayling Sentence Completion Test from cohort 1, the Wisconsin Card Sorting Test from cohort 2, and the Behavioral Dyscontrol Scale from cohort 3.

The Controlled Oral Word Association Test (COWAT) is a measure of verbal fluency that requires subjects to generate words that begin with the letters F, A, and S in three
subsequent 60 second sessions (Benton & Hamsher, 1976). The total number of words was used as the outcome score. One male from cohort 1 was missing a score for the COWAT.

The Stroop Color and Word Test is a measure of response inhibition (Golden, 1978). The color-word section is comprised of names of colors printed in a contrasting ink color (e.g. the word BLUE printed in red ink). The task requires subjects to name the color of the ink rather than read the word. Subjects are given 45 seconds to complete the task. This is the version of the Stroop utilized in the test batteries from cohorts 2 and 3. However, cohort 1 used a slightly different version, the Stroop Neuropsychological Screening Test, which is identical to the version above with the exception that subjects were allowed 120 seconds to complete the task (Trenerry et al., 1989). The number of items completed in the time allowed was used as the outcome variable. Three men from each of the three cohorts were missing scores for the Stroop.

Backward digit span and letter-number sequencing are both measures of working memory and were administered as subtests of the Wechsler Adult Intelligence Scale 3rd Edition (WAIS-III; Wechsler, 1997a) for cohorts 2 and 3 and the Wechsler Memory Scale 3rd Edition (WMS-III; Wechsler, 1997b) for cohort 1. For backward digit span, subjects were verbally provided increasingly longer sequences of numbers and were required to recall the digits in reverse order. For the letter-number sequencing, subjects were verbally provided a sequence of alternating letters and numbers (e.g. Q1B3J2) and were required to recall the numbers in numerical order followed by the letters in alphabetical order. The outcome score for each of these tasks was the raw score. Three men from cohort 2 and one man from cohort 3 were missing scores for backward digit span; three men from cohort 2 and 10 men from cohort 3 were missing scores for letter-number sequencing.

The Hayling Sentence Completion Test Part B is a measure of response inhibition (Burgess & Shallice, 1997). This task requires the subject to complete a sentence with a word that is incongruous with the meaning of the sentence (e.g. “The captain wanted to stay with the sinking…peanut.”). The outcome score for this task was the number of errors.

The Wisconsin Card Sorting Test (WSCT) assesses mental flexibility and involves matching response cards to a set of stimulus cards based on one of three features that changes across the course of administration: the number of shapes on the card, the color of the shapes, or the shapes themselves (Heaton, 1993). The WCST requires the participant to match cards correctly without knowing the sorting principle, being told after each response whether that match was correct or incorrect. After a fixed number (n=10) of consecutive correct matches, the sorting principle changes and the participant must shift to a new sorting strategy. The number of perseverative errors was used as the outcome score. Six men from cohort 2 have missing scores for the WCST.

The Behavioral Dyscontrol Scale (BDS) assesses behavioral self-regulation (Grigsby et al., 1992). The BDS requires subjects to complete seven items, which assess motor performance (two items for simple motor control, 2 items for inhibition, two items for motor learning, and one item for cognition and error detection) and one non-motor item, which assesses the capacity to shift attention. A final item is a rating by the examiner of the patient’s insight into the accuracy of his/her performance. The total BDS score (0-27 points) was used as the outcome score.

**Statistical analysis**

Subjects were assigned to one of two groups based on *FMR1* repeat length: non-carriers (<55 repeats) and premutation allele carriers (55-199 repeats). Table 2 lists age, education, and IQ data stratified by repeat group for individual cohorts and the combined sample.
Education was defined as a 6-level ordinal variable in all statistical models (1=some high school completed/no qualifications, 2=high school completed/O Levels, 3=technical or vocational school completed/A Levels, 4=some college completed/higher diploma, 5=college completed/first degree, and 6=Professional or graduate school completed/postgraduate studies). For descriptive purposes, this variable was collapsed as a dichotomous variable [1=some higher education or less (classes 1, 2, 3, and 4 above), 2=college completed or more (classes 5 and 6 above)] (Table 2). IQ scores were obtained in cohort 1 using the Wechsler Abbreviated Scale of Intelligence (WASI; Wechsler, 1999) and in cohorts 2 and 3 using the WAIS-III (Wechsler, 1997a). Repeat group differences were tested using analysis of variances (ANOVA) for age and IQ and chi-square tests for education. Demographic variables that differed for repeat groups were included in models as potential confounders in addition to indicator variables for cohort.

All executive function scores were analyzed as outcome variables in models with $FMR1$ repeat length as the main predictor, which was used both as a categorical and continuous variable in different analyses. First, repeat length was used as a dichotomous variable in analysis of covariance (ANCOVA) models to compare mean scores between the non-carrier and premutation groups. A Tukey’s post hoc analysis was performed to test for adjusted mean score differences between groups. Second, repeat length was used as a continuous variable in linear regression models to analyze associations between scores and repeat length. For models where repeat length was a significant predictor, interaction terms between repeat variables and covariates were tested.

Two strategies were used to account for differences in Stroop administration between cohorts. In the models outlined above, indicator variables for cohort were included as covariates along with the demographic covariates in order to account for cohort-specific effects. Our second approach was to normalize scores across cohorts rather than include a cohort covariate; cohort-specific Z-scores were calculated and used as the outcome measure.

Whereas the models above query $FMR1$ repeat length as a predictor of executive function score as a continuous variable, we also performed additional analyses to determine whether the premutation allele was associated with low executive function scores, defined as scoring greater than one standard deviation away from the mean on any measure, which might indicate executive function impairment. Means and standard deviations were calculated using scores from the entire sample, including carriers, non-carriers, and all cohorts. Scores from each measure were dichotomized (0=scored higher than one standard deviation below the mean or “unimpaired”, 1=scored lower than one standard deviation from the mean or “impaired”) and logistic regression was performed for each measure to determine whether the premutation group was more susceptible to a low score on executive function measures.

Phenotypes currently known to be associated with $FMR1$ premutation alleles are not fully penetrant. Roughly 20% of female carriers of the premutation develop premature ovarian failure (Sherman, 2000) while roughly 30% of male carriers of the premutation develop FXTAS (Jacquemont, et al., 2004). Further, the penetrance of FXTAS appears to be a function of both age and repeat length, with males over the age of 50 with 70 repeats or more at the highest risk (Jacquemont, et al., 2006). Thus follow-up analyses were performed to test the hypothesis that the presence of executive dysfunction is determined by age and repeat length among premutation males. First, to identify a subset of premutation carriers with low executive function scores as a function of age and CGG repeat length, the subjects were further divided into four repeat groups (non-carrier: <55 repeats; low premutation: 55-70 repeats; mid premutation: 71-100 repeats; and high premutation: >100 repeats) and three age groups (<30 years of age, 30-49 years of age, and ≥50 years of age). The four measures shared across cohorts were tested for a significant interaction between these repeat
and age groups. Second, we compared premutation carriers with and without low executive function scores to determine if the two groups differed for age or repeat length.

All statistical analyses were performed using the PROC REG and PROC GLM procedures on the SAS System for Windows, Release 9.1.

RESULTS

Description of Study Cohorts

We found significant differences for demographic variables within and across cohorts (Table 2). Within cohort 1, the non-carrier and premutation groups differed in education level ($\chi^2=5.89$, p=0.02) and IQ ($t=-2.53$, p=0.01). Within cohort 3, the non-carrier and premutation groups differed in age ($t=-2.19$, p=0.03). Across the three cohorts, the non-carrier and premutation groups differed in age (ANOVA; non-carrier: F=91.12, df=2, p<0.01; premutation: F=40.12, df=2, p<0.01), education (non-carrier: $\chi^2=69.84$, df=10, p<0.01; premutation: $\chi^2=48.08$, df=10, p<0.01), and IQ (ANOVA; non-carrier: F=7.71, df=2, p<0.01; premutation: F=3.98, df=2, p=0.02). In addition, the cohort 1 premutation group had significantly longer repeat lengths than did the cohort 3 premutation group (Wilcoxon Signed-Rank Test statistic=1166, p<0.01).

FMR1 repeat length as a predictor of executive function scores

Table 3 summarizes the results of models using FMR1 repeat length as the main predictor of executive function scores, with categorical models using a repeat length group variable (non-carrier vs. premutation carriers) and linear models using repeat length as a continuous variable. Models were adjusted for age, education, and cohort effects. IQ was not included as a covariate as it was highly correlated with education (r=0.49, p<0.01). However, it should be noted that models run with IQ as a covariate rather than education did not change the conclusions of the analyses (data not shown).

In categorical models, the premutation group scored statistically significantly worse compared to non-carriers on the Stroop (partial $R^2=2\%$, p=0.01), the Hayling (partial $R^2=12\%$, p<0.01), and the BDS (partial $R^2=7\%$, p=0.03). Significant linear associations between FMR1 repeat length as a continuous variable in were detected for the Stroop (partial $R^2=2\%$, p=0.02) and Hayling (partial $R^2=12\%$, p<0.01). The partial $R^2$ values were used to calculate Cohen’s $f^2$, a measure of effect size (J. Cohen, 1992). We obtained $f^2$ values of 0.02, 0.14, and 0.08 for the Stroop, Hayling, and BDS scores, respectively, indicating small effect sizes of FMR1 on these scores (J. Cohen, 1992).

To determine whether the significant associations between repeat length and executive function scores detected in the models above were modified by age or education, we tested interaction terms between these variables and repeat length for the Stroop, Hayling, and BDS. Age modified the effect of FMR1 on Hayling scores in both categorical (p=0.01) and linear models (p<0.01), with premutation carriers scoring worse with age compared to non-carriers. Age also modified the effect of FMR1 on Stroop scores for the linear models only (p=0.01), with participants scoring significantly worse with age as a function of increasing repeat length. Age did not modify the effect of FMR1 on BDS scores (data not shown). Level of education did not modify the effect of FMR1 on any of the scores (data not shown).

Because of the difference in test administration of the Stroop across cohorts (see METHODS), we conducted several analyses to examine potential cohort-specific effects. All Stroop models discussed above used raw Stroop outcome scores and were adjusted for cohort using an indicator variable covariate. In addition to FMR1 acting as a significant predictor of Stroop scores (Table 3), this cohort variable was a significant predictor for both
categorical (p<0.01) and linear models (p<0.01). Analysis of interaction terms also indicated that cohort was a modifier of the significant association between Stroop scores and repeat length in linear models (p=0.03), thus we analyzed each cohort separately. In categorical models, premutation carriers did not score differently than non-carriers within cohorts 2 (p=0.57) or 3 (p=0.34), but did score differently within cohort 1 (p=0.01). In linear models, repeat length was not a significant predictor of scores within cohorts 2 (p=0.71) or 3 (p=0.64), but was a significant predictor of scores within cohort 1 (p<0.01). In the event that cohorts 2 and 3 were limited by power to detect a significant difference between the non-carrier and premutation groups, we combined data from these two cohorts and did not detect a group difference (p=0.31). In separate follow-up models, we used a different approach to adjust for this cohort effect by creating cohort-specific z-scores to normalize scores across all cohorts, rather than using raw scores as the outcome variable and adjusting for cohort as in the models above. In new models of the combined sample of all cohorts using these z-scores as the outcome variable, we found that the premutation group scored significantly lower than non-carriers (p=0.03).

FMR1 premutation allele as a predictor of “impaired” executive function

Executive function scores were dichotomized to indicate “impaired”, defined as scoring greater than one standard deviation from the mean, and “unimpaired”. Using logistic regression models, premutation group was not associated with a higher risk of “impaired” scores on any executive function measure adjusting for age, education and cohort (Table 4).

Identification of subset of premutation carriers at highest risk for “impaired” executive function

In secondary analyses to determine whether there was a subset of premutation carriers at a higher risk for “impaired” executive function scores based on repeat length or age, variables coding for four repeat groups and three age groups were created, and interaction terms between these group variables were tested (Table 5). Age by repeat length interaction terms were not significant for COWAT, backward digit span, and letter-number sequencing. However, this interaction between repeat and age groups was significant for the Stroop (p=0.01), with the largest repeat group (>100 repeats) scoring significantly worse than the non-carrier group (<55 repeats) in the oldest age group (≥50 years) only (p=0.0072).

In analyses of premutation carriers only, subjects who scored in the “impaired” range had significantly lower repeat lengths than those that scored in the “unimpaired” range for the Stroop test only (p=0.01). No differences in age were detected for premutation carriers who scored in the “impaired” range compared to the “unimpaired” range for any test (data not shown).

DISCUSSION

The present study represents the largest study sample to date of males who carry an FMR1 premutation allele and are asymptomatic for FXTAS. Our study compiled data from three independent cohorts totaling 100 carriers and 216 non carriers. The main objective was to assess scores from four executive function measures shared across the three cohorts. Based on this collective analysis across shared measures, evidence for a generalized vulnerability for executive function deficits among premutation carriers was not detected, which is consistent with previously reported studies among female carriers (Bennetto et al., 2001; Franke et al., 1999). Although we did not detect any significant associations between the premutation allele on the COWA, backward digit span, and letter-number sequencing adjusting for education, age and cohort, we did detect a significant association with the Stroop, a measure of response inhibition for learned information. Further examination of this
association with the Stroop revealed a cohort-specific effect. Specifically, the association was limited to cohort 1, in which the protocol allowed subjects an additional 75 seconds to complete as many items as possible in contrast to that for cohorts 2 and 3 where subjects were given 45 seconds. One potential explanation would be that the additional time allowed for this version of the Stroop captured increased attentional fatigue with poor inhibitory control which manifested as poorer performance among premutation carriers compared to non-carriers in this study sample.

A secondary objective of this study was to assess additional measures unique to each cohort: the Hayling Sentence Completion Test for cohort 1, the Wisconsin Card Sorting Test for cohort 2, and the Behavioral Dyscontrol Scale (BDS) for cohort 3. We detected associations between the premutation and the Hayling, and the BDS, as previously published (Brega, et al., 2008; Cornish, et al., 2008; Grigsby, et al., 2008). In addition, an age by group interaction was reported for the Hayling task, such that premutation males, asymptomatic for FXTAS, performed disproportionately worse with increasing age compared to performance by control males.

These findings indicate a potential impairment in inhibitory capacity among a sub-set of premutation carriers, consistent with previously published reports that report executive function deficits among premutation carriers (Moore et al., 2004; Sevin et al., 2009). Furthermore, Sevin et al (2009) reported cognitive impairments that precede any evidence of FXTAS symptoms among a small proportion of their sample of premutation males.

Emerging neuroimaging data also lends some support to the notion that the premutation may confer some risk for cognitive dysfunction. For example, in their recent fMRI study, Hashimoto et al (2010) found significant altered activation of the prefrontal cortex of premutation carriers when performing a simple working memory paradigm particularly in areas known to subserve executive functions including working memory (right inferior frontal, dorsolateral prefrontal, and premotor cortices), despite premutation carriers not scoring significantly different from controls. Developmental imaging data are needed to ascertain whether atypical changes in activation worsen with age or remain stable but slightly decreased across the lifespan in the premutation compared to non-carrier controls.

Overall, we found no general executive function deficit among male premutation carriers, though Stroop and Hayling analyses suggest a potential deficit in inhibitory control among a sub-set of male carriers. Certainly additional research is needed to further investigate inhibition among premutation carriers and identify the potential key factors involved in determining which individuals with the premutation are at greatest risk of exhibiting these inhibitory deficits, and if, indeed these are the same individuals most likely to develop FXTAS. Our exploratory analysis did not provide evidence for repeat size or age group to help define this high risk group. In contrast, other domains of executive function (e.g., working memory and cognitive flexibility) may not be as adversely affected in most premutation carriers and may only become discernable later in adulthood among premutation carriers who go on to develop FXTAS.

There are several limitations to this study presented here. First, each cohort was the product of independently initiated studies that varied in ascertainment methods and exclusion criteria. We accounted for potential confounders by adjusting models for variables that differed between cohorts (e.g. age) as well as an indicator variable for cohort, but there is the potential for additional effects not accounted for here. Second, we focused on measures of executive function that overlapped between the individual test batteries and, though the measures were identical across batteries with the exception of the Stroop task, there is the potential that the measures were administered differently within each cohort. Such differences could confound the results of this study. Lastly, we only used FMR1 repeat

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length as a predictor of executive function in this study, while additional molecular measures (e.g., \textit{FMR1} mRNA level and FMRP production) might be more appropriate modifiers of the phenotypes.

Altogether, these findings highlight the need for future studies exploring specific executive functions among large samples of male premutation carriers. In addition, we hope that our collaboration will encourage more multi-site analyses in future studies, including the development of shared neuropsychological test batteries and ascertainment methods.

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**References**


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Table 1
Details on three cohorts included in the collaboration.

<table>
<thead>
<tr>
<th>Cohort</th>
<th>Citation</th>
<th>Recruitment</th>
<th>Inclusion</th>
<th>Exclusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cornish et al. 2008</td>
<td>United Kingdom Clinical Genetics Services and Fragile X Society</td>
<td>Age 18-50 English-speaking</td>
<td>IQ less than 85, stroke, dementia</td>
</tr>
<tr>
<td>2</td>
<td>Hunter et al. 2008</td>
<td>FXS conferences and support groups, word of mouth, sports events, health fairs, churches</td>
<td>Age 18-50 English-speaking</td>
<td>Active substance abuse/addiction, head trauma with loss of consciousness, meningitis, oxygen deprivation, Multiple Sclerosis, Amyotrophic Lateral Sclerosis, Parkinson’s disease, severe chronic fatigue syndrome, complicated migraines (temporary stroke-like effects) with progressive memory impairment, stroke or brain hemorrhage, brain surgery, seizure disorder, schizophrenia, active use of sedating medications</td>
</tr>
<tr>
<td>3</td>
<td>Grigsby et al. 2008, Brega et al. 2008</td>
<td>FXS study subjects at University of Colorado Denver and University of California Davis, FXS support groups, employees at CU Denver and Health Sciences Center</td>
<td>Over age 40 English-speaking</td>
<td>Significant speech/language deficits that make participation impossible, head trauma with loss of consciousness, epilepsy, demyelinating disease, family history of non-FXS genetic neurologic disorder, other neurologic disorders (e.g., stroke), complex medical comorbidities that may affect cognition, contraindications for MRI scanning (e.g., pacemaker, metal in body), schizophrenia, manic episodes, psychotic depression, alcoholism or significant drug use, medications affecting cognition</td>
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FXS=Fragile X Syndrome
### Table 2

Demographic information for individual cohorts and the combined sample.

<table>
<thead>
<tr>
<th>Cohort</th>
<th>NC (&lt;55 repeats)</th>
<th>PM (≥55)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Median CGG (Q1,Q3)</td>
</tr>
<tr>
<td>1</td>
<td>70</td>
<td>30 (29.31)</td>
</tr>
<tr>
<td>2</td>
<td>104</td>
<td>30 (30.41)</td>
</tr>
<tr>
<td>3</td>
<td>42</td>
<td>30 (29.33)</td>
</tr>
<tr>
<td>All</td>
<td>216</td>
<td>30 (29.33)</td>
</tr>
</tbody>
</table>

NC=non-carriers; PM=premutation carriers; Q1: lower quartile; Q3: upper quartile; SD=standard deviation

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[^a]: Among cohorts, cohorts 1 and 2 significantly differ (p<0.05)

[^b]: Among cohorts, cohorts 1 and 3 significantly differ (p<0.05)

[^c]: Among cohorts, cohorts 2 and 3 significantly differ (p<0.05)

[^d]: Within cohorts, NC and PM groups significantly differ (p<0.05)
Table 3

FMR1 repeat length as a predictor of executive function measures: categorical (non-carrier vs. premutation carrier) and linear models (repeat length as a continuous variable). Models adjusted for age, education, and cohort.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Categorical Models</th>
<th>Linear Models</th>
<th>Linear Models</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Least Squares Means</td>
<td>Repeat group partial R²</td>
<td>p-value</td>
</tr>
<tr>
<td></td>
<td>NC</td>
<td>PM</td>
<td>p-value</td>
</tr>
<tr>
<td>COWAT</td>
<td>41.56</td>
<td>39.45</td>
<td>0.01</td>
</tr>
<tr>
<td>Stroop</td>
<td>63.52</td>
<td>59.66</td>
<td>0.02</td>
</tr>
<tr>
<td>Backward digit span</td>
<td>7.32</td>
<td>7.06</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Letter-number sequencing</td>
<td>11.68</td>
<td>11.34</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Hayling</td>
<td>1.33</td>
<td>2.43</td>
<td>0.12</td>
</tr>
<tr>
<td>WCST</td>
<td>1.94</td>
<td>2.01</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>BDS</td>
<td>20.57</td>
<td>18.84</td>
<td>0.07</td>
</tr>
</tbody>
</table>

NC=non-carrier; PM=premutation carrier; COWAT=Controlled Oral Word Association Test; WCST=Wisconsin Card Sorting Test; BDS=Behavioral Dyscontrol Scale
Table 4

Percentage of FMR1 premutation allele carriers with low scores on executive function measures, defined as scoring greater than one standard deviation away from the mean. Logistic regression models adjusted for age, education and cohort.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Repeat Group</th>
<th>Logistic Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NC</td>
<td>PM</td>
</tr>
<tr>
<td>COWAT</td>
<td>13.5%</td>
<td>22.0%</td>
</tr>
<tr>
<td>Stroop</td>
<td>8.7%</td>
<td>9.3%</td>
</tr>
<tr>
<td>Backward Digit Span</td>
<td>12.1%</td>
<td>13.3%</td>
</tr>
<tr>
<td>Letter-Number Sequencing</td>
<td>9.0%</td>
<td>14.7%</td>
</tr>
<tr>
<td>Hayling</td>
<td>22.9%</td>
<td>10.0%</td>
</tr>
<tr>
<td>WCST</td>
<td>11.0%</td>
<td>15.6%</td>
</tr>
<tr>
<td>BDS</td>
<td>9.5%</td>
<td>27.8%</td>
</tr>
</tbody>
</table>

NC=non-carrier; PM=premutation carrier; CI=confidence interval; COWAT=Controlled Oral Word Association Test; WCST=Wisconsin Card Sorting Test; BDS=Behavioral Dyscontrol Scale
Table 5

Executive function measures stratified by \textit{FMR1} CGG repeat length and age group: sample sizes and mean scores.

<table>
<thead>
<tr>
<th>Repeat Group (# CGGs)</th>
<th>NC: &lt;55</th>
<th>Low PM: 55-70</th>
<th>Mid PM: 71-100</th>
<th>High PM: &gt;100</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Age Group (years)</strong></td>
<td>&lt;30</td>
<td>30-49</td>
<td>≥50</td>
<td>&lt;30</td>
</tr>
<tr>
<td>N</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COWAT</td>
<td>40.60</td>
<td>43.91</td>
<td>40.12</td>
<td>47.78</td>
</tr>
<tr>
<td>Stroop</td>
<td>76.58</td>
<td>68.47</td>
<td>61.87</td>
<td>80.93</td>
</tr>
<tr>
<td>Backward digit span</td>
<td>7.85</td>
<td>7.49</td>
<td>7.03</td>
<td>10.24</td>
</tr>
</tbody>
</table>

NC=non-carrier; PM=premutation carrier; COWAT=Controlled Oral Word Association Test