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# BLAST : a short computerized test to measure the ability to stay on task. Normative behavioral data and detailed cortical dynamics.

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## 1. Abstract

This article provides an exhaustive description of a new short computerized test to assess on a second-to-second basis the ability of individuals to « stay on task », that is, to apply selectively and repeatedly task-relevant cognitive processes. The task (Bron/Lyon Attention Stability Test, or BLAST) lasts around one minute, and measures repeatedly the time to find a target letter in a two-by-two letter array, with an update of all letters every new trial across thirty trials. Several innovative psychometric measures of attention stability are proposed based on the instantaneous fluctuations of reaction times throughout the task, and normative data stratified over a wide range of age are provided by a large (>6000) dataset of participants aged 8 to 70. We also detail the large-scale brain dynamics supporting the task from an in-depth study of 32 participants with direct electrophysiological cortical recordings (intracranial EEG) to prove that BLAST involves critically large-scale executive attention networks, with a marked activation of the dorsal attention network and a deactivation of the default-mode network. Accordingly, we show that BLAST performance correlates with scores established by ADHD-questionnaires.

Keywords: neuropsychological test, normative data, executive functions, attention, ADHD, intracranial EEG, ECoG

## 2. Introduction

The ability to maintain focused attention on a task until its full completion is crucial in many aspects of life, and has become a major topic of interest in several fields including education and professional sport (Kolb *et al.*, 2011; Mangine *et al.*, 2014; Caron, 2015; Diamond and Ling, 2016; Romeas *et al.*, 2016). In most practical situations, however, performance is impaired by Momentary Lapses of Attention or MLA (Weissman *et al.*, 2006), which can last a few seconds or less (Peiris *et al.*, 2006) during which cognitive resources are side-tracked towards processes unrelated to the instructed task (Smallwood and Schooler, 2006). MLA are pervasive in our daily life (Robertson *et al.*, 1997; Killingsworth and Gilbert, 2010) and can have mildly negative to catastrophic effects from missing a crucial word in a complex explanation to hitting a bike rider while driving. MLA can be conceptually interpreted as a disruption of executive attention, as defined by Posner (“the volitional and controlled aspect of the attentional system”) (Rosario Rueda *et al.*, 2005). It implies a goal-driven constraint on

both the sensory input selection and the response selection process, following rules stored in the task-set (Sakai, 2008).

The behavioral characteristics and neuronal substrates of MLA remain to be established. More research has been done regarding a related phenomenon - Mind-Wandering (MW) - with clear evidence that the Default-Mode Network (Raichle *et al.*, 2001) is critically involved (Mason *et al.*, 2007; Christoff *et al.*, 2009; Stawarczyk *et al.*, 2011; Esterman *et al.*, 2013; Poerio *et al.*, 2017). MLA can be arbitrarily short, be caused by external events and mostly reveal themselves through behavior via isolated errors and/or a transient slowing down of reaction time (Weissman *et al.*, 2006). In contrast, MW is still often defined as a more sustained and internally-triggered phenomenon, during which participants are “zoning out”, transiently forget the task and engage into sustained mental simulations (task-unrelated thoughts that they can report on when asked by thought-probes). However, it should be acknowledged that the difference between MLA and MW is becoming increasingly subtle, as some authors propose that any deviation from the task at hand (during which attention “wanders”) could be called “Mind-Wandering” (McVay and Kane, 2010). Yet, most tasks used to study sustained MW episodes are not well-suited to study MLA : in popular designs such as the continuous performance test (CPT) or the Sustained Attention to Response Task (SART) (Bender *et al.*, 2015; Phillips *et al.*, 2015), participants are driven to automatize a specific behavioral response to frequent stimuli, while infrequent stimuli require a different response and failure to withhold the automated behavior in response to rare stimuli are indicative of MW. Such designs are well-adapted to study long and slow drifts away from the task - and their fMRI signature - but short MLA that would occur during frequent stimuli would remain unnoticed, since processing of such stimuli relies on systematic stimulus-response contingency that is largely automated and less vulnerable to executive failure.

We propose a new task specifically designed to detect MLA, and assess the ability to resist them and « stay on task », on a second-to-second basis : BLAST (Bron Lyon Attention Stability Task) measures the ability to activate selectively the right set of cognitive processes to continuously perform a short task with optimal performance, during one or two minutes, that is the duration of many task-units which require continuous and undivided attention (listening to a complex explanation, reading one or two pages of a book or playing a point in tennis). Such task-units are ubiquitous in daily life, and most longer tasks can be broken down into consecutive units of such duration, with little breaks in between. BLAST reveals fluctuations of attention within such units, with a temporal resolution on the order of one second; in that sense, it markedly differs from classic neuropsychology pen-and-pencil papers assessing attention only globally over the whole test. This is especially important as the variability of reaction times is increasingly used as a measure of attention instability for the diagnosis of attention deficit hyperactivity disorder (ADHD) (Tamm *et al.*, 2012; Gmehlin *et al.*, 2016) .

The paper combines three studies in one: a) an in-depth analysis of behavioral data in a large population of children and teenagers (>800) which reveals the main factors impacting attention stability (age, sex, ADHD-scores), b) normative behavioral data stratified by age from a larger (>6000) population aged 8 to 70 and c) a detailed analysis of the large-scale and highly dynamic cortical network supporting BLAST, from the most precise neural recordings available in humans (intracranial EEG).

### 3. Participants and materials

#### 3.1. Behavioral study

Behavioral data were collected in schools (SCHOOL database) from 859 participants (446 females, 103 left-handers), aged 8 to 18, all free of psychiatric/neurological disorders and with an appropriate behavior during the test (silent, showing no obvious lack of motivation). Participants performed the task on iPads wearing headphones and facing a wall with no view of each other, in groups of one to four, in a large classroom. Sessions lasted one hour to include BLAST, plus several variants of the main task (see tasks description). The study was approved by a national ethical committee (IRB00003888 - FWA00005831).

In addition, a larger normative sample was collected within a science exhibit (« expo cerveau » - cité des sciences de la Villette, Paris) where BLAST was proposed as an interactive test to evaluate the visitors' ability to resist endogenous distractions. The test comprised a series of 30 trials, after a learning stage of 15 trials. Immediately after task completion, visitors indicated their age, gender and whether they had been distracted by external events. The MUSEUM database consists of 6954 participants under 70 (4049 females) reporting no external distractions (74% of 9446 visitors).

### 3.2. *Electrophysiological study*

Intracranial EEG recordings (iEEG) were obtained from 32 patients (19 women, mean age: 28.7, Std: 8.6) candidate for epilepsy surgery. Two patients were not able to perform the task and were excluded from the analysis. Participants were stereotactically implanted with multilead EEG depth electrodes following the classic clinical procedures of the neurological hospitals in Grenoble and Lyon. They had previously written informed consent to participate in the study and experiment have been approved by the local ethical Committee of Grenoble Sud-Est V (Study 0907 - ISD et SEEG, CPP 09-CHUG-12).

Five to seventeen semi-rigid electrodes were stereotactically implanted in each participant. Each electrode was a linear array with a diameter of 0.8 mm, and included between 5 and 18 contact leads along its shaft (2mm wide, with a 3.5 mm center-to-center spacing between consecutive leads) (DIXI Medical, Besançon, France). The precise anatomical location of each lead was measured from patient's individual pre-implant MRI, co-registered with post-implant MRI using an in-house BrainVisa plugin (IntrAnat), that enables the trajectory reconstruction of precise models of the SEEG electrodes onto post-implant MRI (see BrainVisa, brainvisa.info).

Intracranial EEG (iEEG) was recorded with standard 128-channels and 256-channels iEEG acquisition system (Micromed, Treviso, Italy), with a reference in the white matter. Data were bandpass-filtered online [0.1-200 Hz] and sampled at a minimal frequency of 512 Hz, then re-referenced offline by subtracting for each site the signal recorded 3.5 mm away on the same linear electrode (the nearest neighbor : bipolar montage).

Signals were visually inspected with an in-house, freely downloadable software package for electrophysiological analysis (ELAN-pack) (Aguera *et al.*, 2011) to reject leads and trials with epileptiform activity, including all sites considered by clinicians to be in the epileptogenic zone (leading to the rejection of an average of 10% of the recording sites in individual patients). High-Frequency Activity [50-150 Hz], or "high-gamma activity", was extracted with in-house scripts in Matlab (the Mathworks, inc) following our usual procedure (Ossandón *et al.*, 2012). That procedure can be summarized as follows: bipolar iEEG signals are first bandpass-filtered in ten consecutive 10-Hz-wide frequency bands (50-60 Hz, 60-70 Hz, ..., 140-150 Hz). Each of those ten bandpass-filtered signal is then transformed into its envelope using a standard Hilbert transform and each envelope is then expressed in % of its mean value (as calculated across the entire experiment). In other words, each envelope time series is simply divided by its mean across the entire recording session and multiplied by 100. In the last step, the ten normalized envelope signals (in %) are averaged together (across the ten frequency bands) to provide one single time-series: the High-Frequency Activity [50 to 150 Hz], or HFA. Significant stimulus-induced HFA variations are detected statistically by comparing HFA for each time sample [between 0 and 3000 ms relative to the first stimulus of a trial] with the mean HFA during a [-200 ms : 0 ms ] prestimulus baseline (Wilcoxon signed rank test followed by a False-Discovery Rate correction across all time bins and electrodes with  $p = 0.05$ , following our classic procedure, Genovese *et al.* 2002). HFA measured in specific windows following the initial stimulus (e.g. [100 ms : 200 ms post stimulus onset]) is compared across experimental conditions using nonparametric Kruskal-Wallis tests (FDR correction with  $p = 0.05$ ).

Dynamic, group-level visualizations of task-induced HFA variations onto the standard Montreal Neurological Institute (MNI) single-subject brain were performed with HiBoP (Human Intracranial Brain Observations Player), a new iEEG visualization software developed in our laboratory within the Human Brain Project, which will be released freely in the coming year.

### 3.3. *tasks description*

#### 3.3.1. BLAST

BLAST repeatedly asks participants to find a target letter (the Target) in a subsequent two-by-two array of four letters (the Array), with new letters every trial (Target and Array) (Fig.1). Each trial starts with the presentation of the Target for 200 ms, followed by a mask (#) replaced after 500 ms by the Array (which stays on screen until the manual response). The next trial starts after a pause of 800 ms if the previous response was correct (with a central fixation symbol #), 4800 ms if it was incorrect (which corresponds to a time penalty of 4000 ms) and 3800 ms if the participant did not respond. The penalty system encourages participants to respond only if they are sure of their choice. Experiments were run on a tactile tablet for the SCHOOL and MUSEUM populations: participants were instructed to hold both hands slightly above the screen, on each side of the letter display, and give a gentle touch with their dominant hand (resp. non-dominant hand) when the target was absent (resp. present). During iEEG recordings, patients performed BLAST on a PC synchronized with the EEG acquisition system (The experiment was performed using Presentation® software (Version 18.0, Neurobehavioral Systems, Inc., Berkeley, CA); they pressed gamepad buttons with their left or right index finger (using the same "dominant/non-dominant hand"- "no/yes" mapping as participants of the SCHOOL and MUSEUM populations). Letters were presented foveally in black on a light gray background. Motor responses were immediately followed by a 50 ms auditory beep signal indicating success or failure (one sound for each outcome), at comfortable hearing level. The sequence of « target present » and « target absent » trials was pseudorandom, with the same number of trials for both types. Performance was measured on a total of 30 trials, for a total duration around one-minute (depending on reaction times).

The global instruction was to settle in a steady and reasonably fast pace while avoiding errors (with an explicit analogy to car drivers who avoid accidents at all costs, but nevertheless move forward at a decent speed). The time penalty was precisely to discourage risky strategies, and to minimize the distraction caused by errors and negative feedbacks on subsequent trials: participants were given time to refocus.

< figure 1 about here >

#### 3.3.2. Variations of BLAST: adding and removing cognitive components

Participants of the MUSEUM database performed BLAST after a separate training phase of 10 trials. Participants of the SCHOOL database were tested during a one-hour session which included BLAST, plus several additional tasks (C-BLAST, S-BLAST and 8-BLAST, Table.1) defined as follows (Fig.1 and Table 1): C-BLAST ("Color-BLAST") was a simplified version of BLAST, with no memory or visual search component: the Target letter was displayed in red in the Array to pop out when it was present (other letters were black). The instruction was simply to indicate manually if one of the letters in the Array was red (« no » with the dominant hand, and « yes » with the other hand, as in BLAST). S-BLAST ("Side-BLAST") pushed the simplification one step further, with a direct stimulus-response contingency: a singleton red Target was present in all Arrays and participants simply had to touch the screen on the same side as the Target (simple reaction task). In addition, 8-BLAST was designed to be a more difficult version of BLAST with a circular eight-letters Array instead of the square four-letters Array (longer visual search). Trials in all tasks had similar timing parameters (as described earlier).

C-BLAST, S-BLAST and 8-BLAST were used to evaluate the cost and benefit (in reaction time) of adding or removing critical cognitive components to BLAST. More importantly, the C-BLAST and S-BLAST variants were designed to facilitate the association of subcomponents of the neural response occurring at specific latencies with each stage of the BLAST task: encoding, maintenance, visual search and motor response. Such association is based on the timing of each subcomponent and its variation across tasks. For instance, any neural activity that is absent, or weaker, in S-BLAST is not related to the motor response, because S-BLAST involves a response. Also, neural activity associated with the motor response should be time-locked to motor execution. Neural activity related to encoding should occur in

the interval between the target and the array, and should be absent or reduced in S-BLAST and C-BLAST which can be performed without encoding (even if we cannot exclude that some level of automatic encoding occurs in those conditions). Finally, activity starting at the array onset and sustained until the response should be interpreted as participating to visual search, and not to memory maintenance (because maintenance should not be triggered by the array, but by the target) (see supplementary Table I for a schematic dynamic and functional dissociation between BLAST variants).

All variants were performed during a specific session following an adaptive design (see next paragraph). The description of that design, and the presentation of the corresponding results can be found in the next section ("Adaptive version of BLAST").

<b>Population</b>	<b>Versions of BLAST</b>
SCHOOL	BLAST, C-BLAST, S-BLAST, 8-BLAST
MUSEUM	BLAST
SEEG	BLAST, C-BLAST, S-BLAST

**Table 1:** versions of BLAST used for each subpopulation

### 3.3.3. Adaptive versions of BLAST

In schools and during iEEG sessions, C-BLAST, S-BLAST, 8-BLAST (and BLAST, in addition to the standard design described above) were performed in an adaptive, staircase, design, in which participants were asked to achieve a series of five consecutive successful trials, under increasing time pressure. Trials of each task were designed as in BLAST, with the presentation of the Target (200 ms), followed by the mask (700 ms) and the Array until the participant's motor response (i.e. the same timing as BLAST). The overall task design differed from BLAST, however, in order to evaluate how fast a participant could respond under such an accuracy constraint. In the adaptive design, the explicit objective was to achieve series of five consecutive correct trials, faster than an adaptive response time limit which decreased with each successful series, until the participant could no longer succeed. We measured TIME\_LIMIT, the best response time limit s/he could reach and the median of all correct reaction times MEDIAN\_RT\_CORRECT. The response time limit was initialized to 10 seconds, then updated after each successful series to the slowest reaction time of that series, minus a 20 ms decrement (to converge as fast as possible to the participant's response time limit): the participant was challenged to achieve a slightly faster series. Series were immediately interrupted after any response incorrect or too slow (relative to the ongoing time limit), and the new time limit was simply increased by a 20 ms step for a new, easier, challenge. The objective (five trials) is obviously arbitrary: it is a compromise between a goal that is too hard (and would discourage participants) and one that is too easy (and can easily be achieved by chance).

### 3.4. Post-test questionnaires

Participants of the SCHOOL population filled up a questionnaire immediately after the experiment to rate several subjective factors including i) their motivation during the task (MOTIV, on a 1 to 10 scale from 'not motivated at all' to 'extremely motivated'); ii) if they had to focus during the task (FOCUS, on a 1 to 10 scale); iii) how stressed they felt (STRESS, on a 1 to 10 scale); iv) if they felt they had been mind-wandering during the task (MW on a 1 to 4 scale, from "not at all" to "a lot"), and v) if they had been distracted by external noise (NOISE, on a 1 to 4 scale, from « never » to « very often").

Another questionnaire, filled at home by parents, asked about various aspects of the participants' life outside of school, focusing on TV and video-game usage (number of hours) and hobbies (sport and artistic activities). Finally, parents also filled an ADHD rating scale IV home version (DuPaul *et al.*, 1998) based on the global behavior of their son or daughter the past 6 months. This questionnaire includes 18 questions addressing separately two dimensions (inattention and hyperactivity/impulsivity);

it assesses symptoms of attention deficit/hyperactivity disorder (ADHD) according to the diagnostic criteria of the Diagnostic and Statistical Manual of Mental Disorders (DSM IV).

### 3.5. Behavioral indices

During BLAST, reaction time (between the onset of the Array and the response) and accuracy were measured for 30 consecutive trials. Attention stability indices were computed from those measures. Our primary intention was to reveal the propensity to undergo momentary lapses of attention (MLA, or conversely, momentary "peaks of attention"). It led us to depart from standard measures such as the variance of the entire reaction times series, which fails to capture the moment-to-moment dynamics of attention (since the variance might be the same for a participant alternating between highly focused and highly distracted episodes, and another participant mildly focused throughout the task). Clearly, new indices had to be designed to integrate the number, the duration and the local stability of attentive episodes. It is not uncommon to propose several scores for the same test to measure slightly different cognitive components (Christidi *et al.*, 2015). In the following, we describe and motivate the indices we derived from BLAST for neuropsychological assessment. All indices can be adapted to any task with constant difficulty which measures reaction times repeatedly and steadily.

#### 3.5.1. INTENSITY

The first behavioral measure, INTENSITY (figure 2), derives from the natural assumption that highly focused individuals tend to respond fast and with few errors. In other words, a performance graph showing reaction times (y-axis) for all the trials (x-axis) should display long series of hits below a given response time limit  $T$  (horizontal line), even when  $T$  is low (see Figure 3, bottom panel on the left). If we cumulate the length of all successful series below  $T$  (i.e. with a reaction time consistently faster than response time limit  $T$ ), we reach a measure  $P(T)$  which should be high for "highly-focused" individuals even when  $T$  is small (i.e., 500 ms). To penalize errors and to be consistent with the adaptive designs which required participants to generate successful series of five trials (in reference to the description of "adaptive version of BLAST" above), we computed a measure  $P(T)$ , which included only series longer than five consecutive wins, cumulating  $N-5$  « points » for every such series (where  $N$  is the length of that series).  $P(T)$  is the number of points for response time limit  $T$ ; it is computed for every value of  $T$  between 300 ms and 1500 ms (no one could generate series of hits faster than 300 ms). That scoring system penalized errors, as any error interrupted the ongoing series and the participant had to succeed at least five new times before her score increased again. Graph  $P(T)$ , which increases with longer  $T$ , immediately distinguishes visually between several types of participants/strategies (Fig.3) : fast reaction times with many errors ('globally impulsive participants'), slow reaction times with few errors ('globally meticulous'), slow reaction times with many errors ('slow inattentive' type) and fast reaction times with few errors ('fast and focused'). Fast and focused participants are characterized by a large area under the curve  $P(T)$ : for that reason, we defined a behavioral indice of attention,  $INTENSITY = 100 \times AUC(P) / \max(AUC)$ , where  $AUC$  is the area under the curve  $P(T)$  and  $\max(AUC)$  its maximal theoretical value. INTENSITY refers to, and is high for, the "fast and focused" type. One might object that lower values of INTENSITY might not disambiguate the 'impulsive' and the 'meticulous' types, but those two profiles can be differentiated by considering also the median of their reaction times (and graph  $P(T)$ ).

< figure 2 about here >

#### 3.5.2. STABILITY

One limitation of INTENSITY is that it is mathematically lower for participants with slower reaction times (typically, elderly people). Yet, it is clear that someone with slow but close to constant reaction times, and no errors, is fully « on-task ». Therefore, INTENSITY should be complemented with another measure which emphasizes stability more than speed: this is STABILITY (figure 2). STABILITY was derived from the assumption that task-irrelevant cognitive processes add "noise" to

reaction times (Gmehlin *et al.*, 2016): it was thus computed from the "instantaneous" stability of reaction times  $r(\text{trial } i)$ . And since our intention was to minimize the effect of the overall speed, we considered the stability of "normalized reaction times"; i.e. reaction times expressed in % of the median reaction time for the entire task:  $r'(\text{trial } i) = 100 * r(\text{trial } i) / \text{median}(r(\text{all trials}))$ . We defined the instantaneous stability of attention for trial  $i$  as  $\text{instab}(\text{trial } i) = \text{std}(r'(\text{trial } i-1):r'(\text{trial } i+1))$ , it is computed over sliding windows of three consecutive trials for maximal temporal precision. STABILITY was computed from  $\text{instab}(\text{trial } i)$  following a procedure similar to the computation of INTENSITY from  $r(\text{trial } i)$ . To penalize errors as in INTENSITY,  $\text{instab}$  was set to a maximal value (40) for unsuccessful trials. As with INTENSITY, we devised a scoring system  $S(T')$  which accumulates  $N-5$  points for each series of  $N>4$  winning trials for which  $\text{instab}$  stays below  $T'$  (a procedure repeated for  $T'$  values between 0 and a maximum of 40). Graphically,  $\text{instab}$  measures the width of the « tube » in which the reaction time plot seems to be confined locally (i.e. for three consecutive trials) (Fig.2), and  $S(T')$  integrates the length of such series, excluding series shorter than 5 for the same reason as in INTENSITY. In short, STABILITY evaluates the ability to generate long and narrow « tubes » of reaction times:  $\text{STABILITY} = 100 * \text{AUC}(S) / \text{max}(\text{AUC})$ , where AUC is the area under the curve  $S(T')$  and  $\text{max}(\text{AUC})$  its maximal theoretical value.

< figure 3 about here >

### 3.5.3. Other behavioral indices

In addition to INTENSITY and STABILITY, we considered more standard indices such as the overall duration of the task (including time penalties and divided by the number of trials: MEAN\_DURATION), the percentage of incorrect trials (PCT\_ERRORS), the median and the standard deviation of the entire series of reaction time (excluding time penalties: MEDIAN\_RT and STD\_RT). Finally, upon the repeated request of teachers helping with data collection, we designed a measure of the duration participants actually spend "on-task" during BLAST (expressed in % of the task duration). Assuming again that episodes spent "on-task" are characterized by stable and accurate responses, we proposed a measure based on  $\text{instab}(\text{trial } i)$ : FOCUS. FOCUS is the percentage of trials for which  $\text{instab}(\text{trial } i)$  is less than 20 (remember that  $\text{instab}$  is set to 40 for unsuccessful trials). We are fully aware that the cut-off value of 20 is arbitrary: it was chosen after numerous attempts to relate  $\text{instab}$  with self-reports of how participants felt. A special version of BLAST was designed to interrupt the task at any moment and ask participants about their attention. They felt reasonably on task with the feeling of being focused when  $\text{instab}$  was less than 20. Although debatable, a choice had to be made and alternative cut-off values (i.e., 10) resulted in measures highly correlated with FOCUS.

## 3.6. Statistical analysis

Unless specified otherwise, the effect of a given factor (e.g. AGE) was tested using a non-parametric Kruskal-Wallis test (abbreviated KW) with a significance threshold set to 0.01, as Kolmogorov-Smirnov (KS) test revealed general non-normality of our indices. For some analysis, carefully identified in the result section, indices were first normalized within each age group (Z-score normalization: subtract the mean value for that particular age group and divide by the standard deviation), to study the effect of a factor independently of age (e.g. GENDER). This normalization is explicitly mentioned in the text each time it is used.

## 4. Results

### 4.1. Behavioral results

We tested several major predictions: i) that the ability to stay-on-task would increase from children to teenagers and adults, with a plateau in the early twenties at the end of the maturation of the prefrontal cortex and the executive system (Gogtay *et al.*, 2004; Toga *et al.*, 2006) ; ii) that children and teenagers with high inattention scores (according to the ADHD questionnaire) would perform worse than participants matched in age with lower inattention scores, and iii) that attention might be affected



negatively or positively by extra-curricular activities (TV and video-games, art, sport) and by socio-demographic factors (e.g., education level of the parents) (but we found no significant effect, see suppl. Materials). The SCHOOL database was designed to test those predictions, as it combined BLAST behavioral measures with questionnaires filled by parents. In addition, short questionnaires filled by participants at the end of the test allowed us to evaluate whether they had performed the test in good conditions (motivated, with no external distractions) and considered actually BLAST as attention-demanding.

#### 4.1.1. Analysis of post-test questionnaires (self-reports)

BLAST was designed to be attention-demanding and yet pleasant, although not to the degree reached by video-games carefully designed to capture and hold the player's attention. Participants confirmed we reached our goal: a large majority enjoyed BLAST and said they had to focus (MOTIV, "did you enjoy the test? »: 92% above 5, 64% above 7.5 on a 0 to 10 scale; FOCUS, "how focused were you? »: 92% above 5, 69% above 7.5 on a 0 to 10 scale). They also reported little or no distraction by external noises (NOISE: "were you disturbed by external noise? »: 95% below 2 on a 1 to 4 scale, i.e. « never » or « rarely »), which means that our experiment was well-suited to study *endogenous* distraction, as intended.

#### 4.1.2. BLAST scores and ADHD rating scale

A standard ADHD-questionnaire was collected from 692 participants (SCHOOL database), with nine questions related to inattention specifically and nine questions related to hyperactivity (DuPaul *et al.*, 1998). Parents were asked to rate each statement between 0 and 3 (from 0 - « almost never » - to 3 - « very often"), leading to a global inattention score (for nine questions, from 0 to 27), a global hyperactivity score (0 to 27) and a global ADHD score (the sum of the two). We tested for relationships between each global score and each individual question, and all behavioral indices (see supplementary figure 1 for a display of ADHD, Inattention and hyperactivity scores as a function of age and sex).

< figure 4 about here >

To test for possible relationships between global scores and BLAST indices (e.g., INTENSITY, ...), BLAST indices of each participant were transformed into a group letter (H, M or L), indicating whether that participant was in the higher, middle or lower 33% of her age group for that particular index (performance-wise). We tested the Ho-hypothesis that global scores did not differ across groups (H,M,L) and rejected that hypothesis for the global INATTENTION score (KW,  $p < 0.005$ ) for all indices except the error percentage (STABILITY, INTENSITY, FOCUS, MEAN\_DURATION, MEDIAN\_RT and STD\_RT) : participants had a higher inattention score in groups (i.e., letters) with the poorest performance. In contrast, no significant difference between groups were found when considering the global Hyperactivity score. The global ADHD score, which adds the global inattention and hyperactivity scores, differed across groups when considering indices INTENSITY, STABILITY, FOCUS and MEAN\_DURATION (KW,  $p < 0.01$ ) (see figure 4 and table 2 for complete statistics).

Overall, our analysis indicates that BLAST is almost uniquely sensitive to the Inattention component of the ADHD rating scale (a more detailed question-by-question analysis revealed a finer relationship with our indices. more precisely with the observed inability to stay-on-task; see suppl. materials).

	INATT (df = 2)		HYPER (df = 2)		TOTAL (df = 2)	
	KW	p-value	KW	p-value	KW	p-value
INTENSITY	18.96	7e-05	2.81	0.2	10.44	0.005
STABILITY	16.03	0.0003	2.29	0.3	10.73	0.004
FOCUS	15.70	0.0004	4.64	0.1	11.44	0.003
MEAN_DURATION	16.65	0.0002	2.55	0.3	11.98	0.002

STD-RT	14.42	0.0007	0.75	0.7	7.43	0.02
MEDIAN_RT	13.78	0.001	3.80	0.1	5.93	0.05
% ERRORS	4.41	0.1	1.83	0.4	4.59	0.1

**Table 2.** statistical values for all tests reported in paragraph 4.1.2 (BLAST scores and ADHD rating scale). KW = Kruskal-Wallis Chi-squared values.

#### 4.1.4. Normative data and age and sex effects

Normative data were computed from the MUSEUM database and displayed graphically for all behavioral indices in Fig.5 in a form that reveals a clear effect of age. All performance indices were affected by age, including all measures of attention (Kruskal-Wallis,  $p < 10^{-22}$  for all), with a systematic increase of performance with age for participants younger than 25. Participants also reported their gender, and we found significant differences between the two genders on two behavioral indices (Kruskal-Wallis,  $p < 0.01$  for PCT\_ERRORS and MEDIAN\_RT), even when considering normalized scores (relative to same-age participants, see methods). Females were slower than males but made fewer errors (see supplementary figure 2 and table 3 for complete statistics).

	AGE (df = 1)		SEX (df = 1)	
	KW	p-value	KW	p-value
INTENSITY	1075	1e-174	1.55	0.2
STABILITY	416	2e-47	5.76	0.02
FOCUS	447	7e-53	0.69	0.4
MEAN_DURATION	1001	8e-160	0.18	0.7
MEDIAN_RT	2040	0	15.5	8e-5
% ERRORS	265	5e-22	16.3	5e-5

**Table 3.** statistical values for the effect of sex and age on BLAST indices. KW = Kruskal-Wallis Chi-squared values.

< figure 5 about here >

The pervasive influence of age led us to compute and display nine quantiles (10 to 90%, by step of 10%) as a function of age, with a one-year stratification between 8 and 18. A neuropsychologist using the graphs to interpret BLAST scores, should identify the age of the participant on the y-axis and her score on the x-axis, then use the color-code to evaluate immediately the proportion of participants of the same age with a higher score (90,80,70 % ...). Supplementary Fig.3 also show polynomial functions modelling the age effect, where the dependence of quantile values on age was nicely fitted by third-order polynomial functions  $q(\text{age}) = a.y^3 + by^2 + cy + d$ , where  $y = \log(\text{age})$  (polynomial fitting in MATLAB interface, the Mathworks, inc.).

It is worth noticing that none of the distributions is bimodal, for any age group. The distributions of all behavioral indices have only one peak, and any attempt to define a cutoff score to identify impairment ("high" vs "low" attention scores) would be arbitrary and debatable.

#### 4.1.5. Test-Retest

Test-retest reliability was evaluated from data of 122 participants who performed BLAST twice, using two measures: the Pearson's correlation coefficient (Rho) and the intraclass correlation coefficient - (icc; irr package of R with parameters: 'oneway' and 'consistency'). Data are shown in Table 4; unsurprisingly, the most reliable measure is the median reaction time (Pearson Rho = 0.93, icc = 0.90), while most measures reach 0.6 or higher with both methods, with a maximum reliability for INTENSITY (Rho = 0.8, icc = 0.81) and a minimum reliability for MEAN\_DURATION (Rho = 0.49, icc = 0.49). These values are in line with test-retest reliability measures of standard tests of executive functions (Lowe and Rabbitt, 1998) .

	<b>Icc (all)</b>	<b>R pearson (all)</b>
INTENSITY	0.80	0.81
STABILITY	0.65	0.65
FOCUS	0.52	0.55
MEAN_DURATION	0.49	0.49
STD-RT	0.60	0.61
MEDIAN_RT	0.90	0.93

**Table 4:** Test-retest reliability for the main behavioral indices of BLAST performance.

#### 4.1.6. Comparison of BLAST and CODE

Thirty-seven participants of the same age group (16-17) performed both BLAST and a standard pencil-and-paper test of sustained attention (CODE), a subtest of processing speed index from the Wechsler Intelligence Scale for children and the Wechsler Adult Intelligence Scale respectively WISC-IV and WAIS-IV (Wechsler, 2003, 2008). CODE consists in matching symbols to numbers as quickly as possible during two minutes, according to written instructions. We found significant correlations between CODE (number of correct responses) and most behavioral indices of BLAST: INTENSITY (Spearman Rho Correlation Coefficient = 0.57,  $p = 0.0002$ ); STABILITY (Rho = 0.48,  $p = 0.002$ ); MEAN\_DURATION (Rho = -0.59,  $p < 1e-5$ : participants better at CODE were faster at BLAST); FOCUS (Rho = 0.61,  $p < 1e-5$ ); MEDIAN\_RT (Rho = -0.55,  $p = 0.0004$ ); PCT\_ERRORS (Rho = -0.39,  $p < 0.05$  - less errors at BLAST for higher scores at CODE).

#### 4.1.7. One minute or ten minutes?

Considering that BLAST lasts only about one minute - in its thirty-trials version - one might question its validity to assess the ability to stay on task for longer durations, over segments of ten minutes for instance. One might argue that individuals who can remain sharply focused for one minute are not necessarily the same who can perform steadily for ten minutes. We addressed this question with a database of 121 participants aged 10-12 (65 males) performing a 200 trials version of BLAST (separate from the SCHOOL and MUSEUM datasets and participants). We computed our main indices over the first 30 trials and correlated their values with the same indices measured over the entire session (200 trials), Table 5 contains the result, as well as the same correlation analysis when considering the first 40, 50 and 60 trials. We found that for several indices (INTENSITY, MEAN\_DURATION and MEDIAN\_RT), the correlation (Pearson's correlation coefficient) was already high for 30 trials (0.75, 0.75 and 0.87 respectively), meaning that the ability of an individual to be fast and focused during ten minutes could be fairly well estimated in one minute only. The full analysis suggests that the STABILITY and FOCUS indices over ten minutes should rather be estimated with a 50 trials version of BLAST ( $R = 0.78$  and  $0.67$  respectively). The conclusion that long-term (10 minutes) attention stability can be estimated in around one minute has important bearings for neuropsychologists who must often perform testing sessions under strong time-constraints (Fig. 6).

< figure 6 about here >

	<b>30 trials</b>	<b>40 trials</b>	<b>50 trials</b>	<b>60 trials</b>	<b>200 trials</b>
INTENSITY	0.75	0.81	0.86	0.88	1
STABILITY	0.58	0.68	0.78	0.81	1
FOCUS	0.53	0.62	0.67	0.71	
MEAN_DURATION	0.75	0.81	0.84	0.86	
MEDIAN_RT	0.87	0.87	0.90	0.92	

**Table 5 :** Correlation between behavioral indices measured over 200 trials, and the first 30, 40, 50, 60 trials of BLAST respectively (Pearson’s correlation coefficients).

## 4.2. Electrophysiological Study

This section describes the large-scale cortical dynamics during individual trials of BLAST and its variants, from the onset of the target letter to the motor response, with a millisecond and millimetric precision. Our strategy was to identify all major brain regions supporting BLAST from iEEG HFA<sub>[50-150 Hz]</sub> data and examine the specific dynamic of activation of each of those Regions of Interest (ROI) from iEEG of individual patients. The main objective was to associate precise cortical regions with each of the three main cognitive components of BLAST: i) encoding and maintenance of the Target letter, ii) visual search of the Array, iii) motor response, which can be done by comparing HFA induced by BLAST and variants of BLAST lacking one or several of those components (C-BLAST and S-BLAST) (see §3.3.2 for details). We report only ROIs where similar activation patterns were observed in at least two different patients, following our standard procedure for iEEG analysis (Lachaux *et al.*, 2012). Note that we don’t report cortical regions with unspecific visual responses (so as to avoid including the entire visual cortex). Also, our analysis does not include subcortical responses, which might play an important role in BLAST but were not recorded. Finally, all sites with pathological activity and/or within the seizure onset zone were carefully excluded from the analysis.

We found only seven ROIs with increased HFA during BLAST relative to baseline (see table 6 for a complete overview with both uncorrected - Wilcoxon,  $p < 0.01$  – and FDR-corrected results, with exact anatomical locations relative to landmarks identified on individual MRIs and based on the nomenclature of (Donkelaar Ten et al. 2018)): the left Inferior Temporal Gyrus (ITG), the left ventral PreMotor Cortex (vPMC), the right and left dorsolateral PreFrontal Cortex (DLPFC), symmetric portions of precentral gyrus/sulcus left and right (PreC), a region extending bilaterally over the Supplementary Motor Area and the anterior Cingulate Cortex (ACC/preSMA), the IntraParietal Sulcus (IPS) on both sides and the right Frontal Operculum (F Oper). In addition, five ROIs showed a reverse pattern of HFA *decrease* during BLAST: the middle Temporal Gyrus in the Lateral Middle Temporal Cortex (MTC), the OrbitoFrontal Cortex (OFC), the ventromedial PreFrontal Cortex (VMPFC), the Temporal Parietal Junction (TPJ) and the Posterior Cingulate Cortex (PCC), all bilaterally. Figure 7 summarizes the location of those Regions of Interest and the timing of their activation/deactivation.

	Sites / Patients	Mni Box	Anatomical Landmark
<b>ACTIVATIONS</b>			
L ITG	3[3] / 3 - 3	[-54 : -67] <sub>x</sub> [-50 : -47] <sub>y</sub> [-16 : -18] <sub>z</sub>	Inferior Temporal gyrus
L IPS	3[3] / 3 - 3	[-29 : -38] <sub>x</sub> [-46 : -35] <sub>y</sub> [ 34 : 43] <sub>z</sub>	Intra-Parietal sulcus
R IPS	3[3] / 3 - 3	[ 25 : 30] <sub>x</sub> [-60 : -57] <sub>y</sub> [ 44 : 49] <sub>z</sub>	idem
L PreC	3[3] / 3 - 3	[-37 : -54] <sub>x</sub> [-12 : -3] <sub>y</sub> [ 43 : 51] <sub>z</sub>	Upper precentral gyrus/sulcus
R PreC	3[3] / 3 - 3	[ 52 : 54] <sub>x</sub> [ 2 : 3] <sub>y</sub> [ 31 : 34] <sub>z</sub>	idem
L ACC/preSMA	2[2] / 2 - 4	[-11 : -12] <sub>x</sub> [ 6 : 16] <sub>y</sub> [ 48 : 52] <sub>z</sub>	Region between the cingulate/paracingulate sulci
R ACC/preSMA	6[5] / 4 - 6	[ 7 : 10] <sub>x</sub> [ 0 : 15] <sub>y</sub> [ 30 : 52] <sub>z</sub>	idem
L DLPFC	2[2] / 2 - 2	[-41 : -50] <sub>x</sub> [ 21 : 26] <sub>y</sub> [19 : 24] <sub>z</sub>	Inferior Frontal Sulcus
R DLPFC	3[3] / 3 - 3	[ 37 : 44] <sub>x</sub> [ 23 : 33] <sub>y</sub> [ 6 : 16] <sub>z</sub>	idem
L VPMC	6[6] / 6 - 6	[-46 : -54] <sub>x</sub> [-1 : 5] <sub>y</sub> [ 14 : 23] <sub>z</sub>	Lower precentral sulcus, posterior to Broca area
R F Oper	2[2] / 2 - 2	[ 37 : 50] <sub>x</sub> [ 14 : 23] <sub>y</sub> [ 4 : 12] <sub>z</sub>	Frontal Operculum
<b>DEACTIVATIONS</b>			
L OFC	3[2] / 4 - 3	[-33 : -37] <sub>x</sub> [ 37 : 43] <sub>y</sub> [-17 : -15] <sub>z</sub>	Orbital sulcus
R OFC	5[4] / 4 - 5	[ 36 : 49] <sub>x</sub> [ 28 : 46] <sub>y</sub> [-12 : -10] <sub>z</sub>	idem
L VMPFC	5[2] / 4 - 5	[ -7 : -17] <sub>y</sub> [ 39 : 55] <sub>y</sub> [-16 : -4] <sub>z</sub>	Paracingulate and anterior rostral sulcus
R VMPFC	7[7] / 6 - 7	[ 3 : 13] <sub>x</sub> [ 26 : 57] <sub>y</sub> [-27 : -3] <sub>z</sub>	idem
L PCC	7[5] / 9 - 7	[-6 : -16] <sub>x</sub> [-59 : -37] <sub>y</sub> [ 25 : 38] <sub>z</sub>	Posterior Cingulate sulcus
R PCC	7[3] / 7 - 9	[ 7 : 12] <sub>x</sub> [-49 : -36] <sub>y</sub> [ 29 : 42] <sub>z</sub>	idem

L MTC	16[10] / 9 - 16	[-51 : -65] <sub>x</sub> [-47 : -13] <sub>y</sub> [-29 : -3] <sub>z</sub>	Inferior and Superior Temporal sulci
R MTC	10[4] / 9 - 11	[ 53 : 65] <sub>x</sub> [-39 : -3] <sub>y</sub> [-19 : -3] <sub>z</sub>	idem
L TPJ	1[1] / 4 - 4	[-44 : -64] <sub>x</sub> [-51 : -45] <sub>y</sub> [ 36 : 57] <sub>z</sub>	Ascending branch of Superior Temporal Sulcus
R TPJ	6[1] / 5 - 6	[ 52 : 63] <sub>x</sub> [-46 : -36] <sub>y</sub> [ 29 : 50] <sub>z</sub>	idem

**Table 6.** Exact location of all cortical regions activated and deactivated during BLAST. **Nb Sites / Patients** : number of sites with significant activation or deactivation, with the following code : “ 7[3] / 8 – 9 ” means that 7 sites were found significant without FDR correction, 3 after FDR correction, in 8 different patients, out of 9 sites in that anatomical landmark. **Box Mni** : area containing all sites of the Region of Interest in the MNI space. **Anatomical landmark** : precise anatomical location where effects were observed. Abbreviations : ITG = Inferior Temporal Gyrus; IPS = IntraParietal Sulcus; PreC = PreCentral Gyrus/Sulcus; ACC = Anterior Cingulate Cortex; preSMA = preSupplementary Motor Area; DLPFC = Dorso-Lateral PreFrontal Cortex; VPMC = Ventral Premotor Cortex; F Oper = Frontal Operculum; OFC = OrbitoFrontal Cortex; VMPFC = Ventral Medial PreFrontal Cortex; PCC = Posterior Cingulate Cortex; MTC = Middle Temporal Cortex; TPJ = TemporoParietal Junction; L/R = Left/Right.

< figure 7 about here >

The portion of the left ITG active during BLAST matched the location and functional specificity of the word-form area, WFA, a region of the left inferior temporal gyrus supporting visual processing of letters and letter-strings (Sup. Fig. 5). The dynamics of activation during BLAST revealed two phases: during the presentation of the Target and during the display of the Array, as expected in response to letters. However, the statistical comparison of BLAST and its variants C-BLAST and S-BLAST revealed that the response to the letter was strong and sustained only when the Target must be encoded into working memory (BLAST) (Sup Fig. 5). It was also stronger when the Array was searched attentively (i.e. in BLAST). Therefore, the WFA participated actively to both the encoding phase and the search phase of BLAST.

Reactive sites in the DLPFC (i.e. sites with a significant HFA deviation relative to baseline) were located in the Inferior Frontal Sulcus and were especially active during the Array presentation with a stronger activity when the participant took longer to respond, compatible with a role in the target detection process (Sup Fig. 6 and 7). The left vPMC (sites in the lower part of the precentral Sulcus immediately posterior to Broca) and the right frontal Operculum reacted to both the Target and the Array, particularly in the BLAST condition (Sup Fig. 6 and 7). Note that the letter stimulus has the same physical characteristics in BLAST, C-BLAST and S-BLAST, but carries task-relevant information only in BLAST, in which it must be encoded and maintained in short-term memory to serve as a template for the visual search. Single trial representation (matrix representation in Sup Fig. 6 and 7) shows that activity was sustained continuously until task completion in the Frontal Operculum, but extended beyond the reaction time in the vPMC, suggesting a participation to motor programming and execution for that region in addition to the more cognitive aspects of BLAST. Figure 8 displays the comparative timing of activation of ROIs recorded in the same patient (for two patients) : the data largely confirm for instance that areas involved in the visual search process have different functions, as we just described. For example, the DLPFC and Frontal Operculum peaks occur much earlier than in the vPMC. In fact, a careful examination of Sup Fig 6 and 7 reveals that activity of the former return towards baseline level before the motor response, while the vPMC response extends hundreds of millisecond later. Additional subtler differences in timing between regions are harder to interpret but indicate a sequence of processing across cortical areas rather than a fully integrated network acting as one functionally unified block.

< figure 8 about here >

All other ROIs stopped their activity upon task completion. The activation of the IntraParietal Sulcus (IPS) occurred mostly during the Array with a stronger response in the two BLAST variants with a red singleton in that Array (Sup Fig. 7), compatible with a role of that region in spatial attention shifts and attentional capture by salient stimuli. It might also participate in a large-scale top-down process to

sustain activation in letter-specific areas of the inferior Temporal Lobe, as part of a larger Dorsal Attention Network (Corbetta and Shulman, 2002), which also includes the Frontal Eye Field, or FEF. Accordingly, the large Precentral region of interest (PreC) included sites compatible with the location of the Frontal Eye Field (see Precentral, Sup Fig. 7), with a response specific to Targets which must be encoded into working memory (BLAST), and must therefore be attended.

Similar patterns of activation were observed in the ACC/preSMA (Sup Fig. 7), between the cingulate and paracingulate sulci. This region, with the DLPFC, is a hallmark of the frontal executive system which mediates cognitive control and goal-directed behavior in general, and the ability to stay-on-task in particular. Unsurprisingly, both ROIs were active during the encoding and during the search phase, with a steady activity increase in the latter until task completion.

In the five ROIs deactivated by BLAST, HFA suppressions observed in individual patients revealed a stronger deactivation in the most difficult task (BLAST) in most instances (Sup Fig. 8). They had a slow dynamics with a negative peak while participants processed the Array. Single trial matrixes suggest that the five ROIs might have different temporal characteristics; but HFA decreases, although significant, were not sufficiently strong to elaborate further on their dynamics, in contrast with the massive HFA increases seen in other ROIs. All ROIs deactivated during BLAST are part of the Default-Mode Network (Raichle *et al.*, 2001), in line with recurrent observations that activity is suppressed in the DMN when processing external stimuli attentively.

## 5. Discussion

Our objective was to propose a test that measures « the ability to stay on-task », with a well-identified cortical network and age-stratified normative data. We focused on the ability to apply consistently and selectively the set of cognitive processes necessary and sufficient to perform the task at hand, with no interference from irrelevant processes. BLAST (Bron/Lyon Attention Stability Test) is to our knowledge the first test meeting all such requirements, with a performance that is related selectively to inattention, not hyperactivity. In addition, intracranial EEG data provide clear evidence that BLAST involves primarily the frontal executive and dorsal attention network, including all major components of the executive attention system in the prefrontal cortex, together with a reduction of activity in the Default-Mode Network.

### 5.1. *Task design*

We argue here that there are very few possible alternatives to BLAST, in terms of task-design, to measure attentional stability with a close-to-second temporal resolution. BLAST provides a reaction time every two seconds on average, which defines the temporal precision at which fluctuations of attention can be detected. It matches the time-scale of short MLA which can make us « miss » an important word in an explanation, for instance. It is hard to imagine a task with a better temporal precision, considering the minimal duration of cognitive stimulus-to-response cycles (Madl *et al.*, 2011) and the constraint to avoid muscular fatigue. In theory, a finer time resolution could be achieved if participants had to react continuously to a changing stimulus (with a continuous behavioral response, as when tracking a moving dot with a joystick); however, to the best of our knowledge, no such task keeps difficulty constant over time (for instance, in tracking tasks, parts of the trajectory with high, changing curvatures are harder to track than smoother parts), and therefore, performance over time does not depend solely upon the participant's attention. Tasks in which behavioral measures are discrete in time, like BLAST, involve repeated presentations of a sensory stimulus followed by a participant's overt response, at a pace which determines the temporal resolution of the performance measurement. Such discrete tasks must themselves obey several constraints to ensure that performance depends solely (or as much as possible) upon the attention allocated by the participant to the task: i) the inter-stimulus interval should be constant (to keep task difficulty constant) and on the order of one or two seconds to avoid muscular fatigue and allow reasonable time to process the stimulus. Such constraints already allow to define tasks which can successfully be used to detect off-task episodes, such as the Metronome

task (Seli et al., 2013). However, to minimize the possibility of automatization (which would reduce the behavioral impact of lapses of attention), we add the additional constraint that ii) the rule defining stimulus-response association should vary from trial to trial : this implies that participants should be informed of that association-rule before each trial by a cue, shown before stimulus presentation so that cue- and stimulus-processing do not compete for attention resources; and yet iii) the overall task-set (the principle of stimulus-response association) should remain the same throughout the task, as it is known that task-set changes within tasks induce switch costs which affect behavior negatively independently of attention. This set of constraints sums up to allow only designs in which in each trial, a cue instructs participants - with a metronomic timing - to process the upcoming stimulus in a unique, but yet stereotyped way, to choose one of several motor responses. In BLAST, the cue is a target letter which instructs participants to decide whether that letter is among the four letters shown 700 ms after that stimulus. The stimulus-response association rule is not rigid (the same stimulus is not always associated with the same motor response), and yet, the task set remains the same throughout the task. Alternatives to BLAST are of course possible to track attention on a second-to-second basis, but we claim that all of them would follow the same organizing principle.

There are of course computerized tests to evaluate the ability to sustain attention over time and help diagnose ADHD, such as the Conners' Continuous Performance Test (Homack and Riccio, 2006) . But none of them was designed to capture brief lapses of attention as only a minority of the trials really require attentive processing. Interestingly, a task-design very similar to BLAST has been used to study the neural mechanisms of visual attention in non-human primates: the task used an array of four tilted bars instead of letters (Buschman and Miller, 2007). But the trials did not repeat as in BLAST and the authors did not study the variability of reaction times.

## 5.2. *Neural correlates of BLAST*

Our electrophysiological study suggests the following scenario during successful trials of BLAST: after an initial and transient response of early visual areas, activation triggered by the Target letter would reach a region of the basal temporal lobe specialized for letter-forms: the Word Form Area or WFA. The WFA would then hold the search template until and throughout the search process (the display of the Array). If the participant strategy implies subvocal rehearsal, the left Ventral PreMotor Cortex adjacent to Broca, possibly in synergy with the Precentral Cluster, would support an additional, phonological, maintenance process using the phonological loop (in agreement with the classic model of verbal working memory (Baddeley, 2000) . The Dorsal Attention Network, or DAN (Corbetta and Shulman, 2002), including the dorsolateral Prefrontal Cortex, the Frontal Eye Field and the Intraparietal sulcus would a) facilitate visual memory maintenance in the WFA (as the DAN has been shown to sustain and bias activity in visual areas via top-down influences, Noudoost *et al.*, 2010; Seidl *et al.*, 2012), and b) guide visual attention within the Array in line with its primary functional role (Corbetta and Shulman, 2002). The DLPFC might orchestrate the encode-then-search process, given its known ability to maintain task-instructions (the "task sets", Sakai, 2008) ) : it would hold the « program » to encode the search template (the Target) in the WFA, then compare sequentially or in parallel each letter of the Array with that template and support the decision process to press with the right or left index finger. Finally, a region at the interface between the pre-SMA and the dorsal Anterior Cingulate Gyrus would ensure that attention is « on-task », in line with its known implication in cognitive control. The final motor response would obviously be produced by the premotor and motor cortex. In that scenario, a sudden increase in reaction times might be due to a less efficient encoding and maintenance of the search template in the WFA (insufficient top-down influences from the DAN), or a discontinuous search process (again, inefficient or insufficient activation of the DAN or the pre-SMA). In terms of timing, the model implies that the WFA should respond immediately to the target, followed by an activation of the DAN that would last until the response, including the IPS, in parallel with an activation of the DLPFC. The ACC/preSMA should increase its activity throughout the task until its completion and the motor cortex activity should be time-locked to the response. In case of subvocal rehearsal, the vPMC should be active shortly after the ITG activity, and throughout the search

process. Data from two patients in which seven and eight sites (respectively) were responsive to BLAST are consistent with that model (Fig. 8).

This global and highly organized activation pattern does not occur in isolation, but together with a somewhat smoother deactivation process of an entire network called DMN (the Default-Mode Network or task negative network: the Temporal Parietal Junction, the posterior Cingulate Cortex, the medial Prefrontal Cortex, the ventral lateral Prefrontal Cortex and the lateral Temporal Cortex) (Raichle *et al.*, 2001). Activity in the DMN is classically associated with spontaneous, task-unrelated cognition, which might interfere with active visual processing of external stimuli, and its deactivation during BLAST was predicted by the literature (Weissman *et al.*, 2006; Li *et al.*, 2007; Esposito *et al.*, 2009; Anticevic A1, Repovs G, Shulman GL, 2010; Mayer *et al.*, 2010; Anticevic, 2013). However, the precision of iEEG reveals a surprisingly dynamic behavior (Sup Fig 8) with a brief reactivation in the ultra-short interval (800 ms) between two consecutive trials, which can be seen as a brief reactivation of DMN functions whenever possible (Lachaux *et al.*, 2008; Ossandon *et al.*, 2012).

To summarize, BLAST exemplifies the interplay between the DAN and the DMN which is typical of sustained and demanding visual attention tasks (Langner and Eickhoff, 2013; Christoff *et al.*, 2016) . It is therefore ideal to study the ability to stay on-task, and follow the dynamic competition between the DAN and the DMN on a trial-by-trial basis, with second-by-second precision.

### 5.3. Possible limitations of BLAST

A first possible objection to the present study is that the cortical network supporting BLAST was identified in patients suffering from epilepsy. Although it is true that their brain can only be considered as a proxy of a healthy brain, that criticism has been addressed repeatedly over the years and detailed responses including precise guidelines have been published (see for instance, Lachaux *et al.*, 2012). In short: researchers analyzing iEEG carefully check that recordings are made outside epileptogenic networks and are free of epileptiform activity; and that similar observations can be made in the same cortical structure in patients with different types of epilepsy and medications. Thanks to such sanity checks, iEEG has become in twenty years a premium methodology to study the neural dynamics of human cognition (Lachaux *et al.*, 2012; Ritaccio *et al.*, 2014), which results are now widely incorporated in our global understanding of human brain functions.

Regarding the task design, one might criticize that BLAST difficulty is not strictly constant across trials, because some letters might be easier to spot than others, because the location of the target within the array (when present) is likely to have an impact, and because it might take longer to figure out that the target is not in the array. We acknowledge such effects fully, but argue - and checked visually - that the variations in reaction times induced by such factors were minimal compared to the effect of momentary lapses of attention. A third possible criticism changes of strategy might cause fluctuations of reaction times independently of attention (for instance, in a change in the speed/accuracy trade-off), but that particular criticism applies to any design using reaction times to assess attention. Our assumption is that changes of strategy should not cause instability of reaction times on a trial-to-trial basis, but rather a slower change with stable periods lasting several trials; therefore, it is likely that short-scale fluctuations in reaction times that we take as a measure of inattention are indeed due to inattention. Finally, we are fully aware that behavioral performance can only provide an indirect estimate of the level of attention allocated to the task; however, one might argue that in real-life situations, it is also performance, not attention in itself, which ultimately matters.

### 5.4. Conclusion

In summary, BLAST provides one of the few possible task designs to measure fluctuations of executive attention behaviorally on a second-to-second basis, and because performance is measured so often, it can provide a first indication of an individual's ability to stay on task in less than a minute, with numerous possible applications (testing the effects of a pharmacological treatment, evaluating the cognitive impact of short pathophysiological events such as epileptic spikes, measuring the benefits of



cognitive rehabilitation or attention training programs, ...). In addition, the comparison of performance between BLAST and its simplified versions can potentially reveal a deficit in a specific cognitive process, such as encoding/maintenance or visual search, which can then be related with specific brain regions thanks to our detailed knowledge of the BLAST cortical network. For basic research purposes, BLAST is also currently used to understand the neural basis of endogenous attention fluctuations and MLA, and the neural correlates of transient performance decrement observed after external distractions or during multi-tasking.

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## Figure legends

**Figure 1 :** General design of BLAST and its variants. The lower panel shows the general structure of a trial with the sequential display of the Target and the Array, and new letters every trial. The duration of the inter-trial mask depends on the participant's response (800 ms when the response was correct, 4800 ms if it was incorrect, and 3800 ms when the participant did not respond). The upper panel shows the specificities of the three main variants of BLAST in the case of a left-handed participant: the only difference with BLAST is the Array screen, with eight letters in 8-BLAST instead of four, four letters in C-BLAST with a salient color for the target when it is present, and four letters in S-BLAST with a red letter every time, indicating which side of the screen must be touched (the same as the red letter).

**Figure 2 :** Scoring systems for INTENSITY and STABILITY. INTENSITY and STABILITY are computed from graphs  $P(T)$  and  $S(T')$  respectively (bottom and top right panels, respectively), from the ratio of the area under the curve (red) divided by the total area of the square englobing that curve (white). The bottom left graph illustrates the calculation of  $P(T)$  from the reaction times for an example value of the response time limit  $T$  (600 ms : 9 points) (« instantaneous » standard deviations of reaction times - computed over three consecutive trials, are shown as gray vertical bars). The procedure is repeated for all  $T$  values between 300 ms and 1500 ms to generate the red plot  $P(T)$ . The top left graph illustrates the calculation of  $S(T')$  from the « instantaneous » standard deviation  $s(\text{trial})$  of the normalized reaction times ( $r'(\text{trial})$ , see methods) for an example value of  $T'$  (20 : 12 points). The normalized reaction times  $r'(\text{trial})$  are simply reaction times expressed as % of the median reaction time.  $S$  is depicted in the top left graph as vertical bars (green =  $s$  less than 10; yellow =  $s$  less than 20; red otherwise, note that  $s$  is set to 40 for every error) and red vertical bars in the upper left graph). The procedure is repeated for all  $T'$  between 0 and 40 to generate red plot  $S(T')$  on the right.

**Figure 3 :** Examples of response profiles for BLAST. The left panel displays reaction times and errors for four participants (same age-group : 16-17 year-old), which correspond to four different response-types (right panel). Type I is fast, steady and accurate and exemplifies what we called FAST AND FOCUSED individuals.  $P(T)$  (right panel) is high for short reaction times and quickly reaches maximal values: most of the square is red. Type II is as fast as Type I, but has many errors (IMPULSIVE type) : consequently,  $P(T)$  mostly colors the bottom end of the square, from fast to slow reaction times. Type III corresponds to the METICULOUS type, with very few errors but slow reaction times.  $P(T)$  mostly colors the right end of the square. Finally, Type IV corresponds to the SLOW INATTENTIVE type, with many errors and slow reaction times. Neuropsychologists might derive a parallel typology from STABILITY graphs.

**Figure 4 :** Distribution of Inattention scores (ADHD rating scale) for low (L, red), medium (M, orange) and high (H, green) performers according to each of the seven indices considered in this study (following the H,M,L grouping procedure defined in paragraph 4.1.2); (geom\_violin graph, ggplot2 library, R). P-values correspond to the Kruskal-Wallis comparisons across groups (H,M,L) as in Table 2.

**Figure 5 :** Age-stratified normative data for the main behavioral indices quantifying the ability to stay on task in BLAST. A neuropsychologist using the graphs to interpret BLAST scores, should identify the age of the participant on the y-axis and his/her score on the x-axis, then use the color-code to evaluate immediately the proportion of participants of the same age with a lower score (90,80,70 % ...).

**Figure 6 :** Comparison of INTENSITY and STABILITY computed over 30 vs. 200 trials. The graphs show values computed over 30 trials (red) versus 200 trials (blue) for INTENSITY and STABILITY for each participant.

**Figure 7 :** Cortical regions activated and deactivated during BLAST. a) anatomical location of the major regions with task-related HFA increases during BLAST (see the table in the main text for precise anatomical information); b) anatomical location of task-related HFA decreases. c) average dynamics of responsive sites in each ROI, expressed in % of the mean HFA value across the entire experiment.

Vertical lines indicate target and array onsets at 0 ms and 700 ms. Experimental conditions are color-coded : blue for BLAST, red for C-BLAST, black for S-BLAST. Activated ROIs are the left inferior temporal cortex (ITG), the left ventral premotor cortex (vPMC), the Dorso-Lateral Prefrontal Cortex on both sides (DLPFC), the right Frontal Operculum (F Operc.), a region encompassing the PreCentral gyrus and sulcus (PreC), a region encompassing the Anterior Cingulate Cortex and the pre-Supplementary Motor Area (ACC/preSMA) and the IntraParietal Sulcus (IPS) on both sides. Deactivated ROIs are the middle temporal cortex (MTC), the orbitofrontal cortex (OFC), the ventromedial prefrontal cortex (vmPFC), the Temporo-Parietal Junction (TPJ) and the posterior cingulate cortex (PCC).

**Figure 8** : Comparative timing of neural activation and deactivation during BLAST. The upper and lower panels display the neural responses in different cortical sites for two representative patients (HFA, [50-150 Hz], normalized for each site to the response peak). Sites are sorted vertically according to their response peak latency. Abbreviations : vPMC = ventral PreMotor Cortex; ACC = Anterior Cingulate Cortex; preSMA = preSupplementary Motor Area; PreCe = PreCentral Gyrus/Sulcus; PCC = Posterior Cingulate Cortex ; TPJ = Temporo-Parietal Junction; FOper = Frontal Operculum; DLPFC = Dorso-Lateral PreFrontal Cortex; IPS = Intra-Parietal Sulcus.

# BLAST : a short computerized test to measure the ability to stay on task : Normative behavioral data and detailed cortical dynamics. Supplementary Material

## BLAST scores and ADHD rating scale : question-by-question analysis

A more detailed question-by-question analysis of the ADHD rating scale revealed a finer relationship with our indices. Since each question was associated with a rating between 0 and 3, we tested for an effect of that rating on normalized BLAST measures (Z-score, relative to age-group, as described in the methods section). We found a significant effect of the rating for 5 of the 9 questions related to Inattention : question 1 (effect on STABILITY, INTENSITY, FOCUS, MEAN\_DURATION, MEDIAN\_RT and STD\_RT,  $p < 0.005$ ) [« Fails to give close attention to details or makes careless mistakes in schoolwork » ]; question 3 (for all indices also,  $p < 0.001$ ) [« Has difficulty sustaining attention in tasks or at play » ], ; question 11 ( $p < 0.005$  for all indices, except STD\_RT) [« Avoids tasks (eg, schoolwork, homework) that require a sustained mental effort » ]. Question 9 had only an impact on STABILITY ( $p < 0.01$ ) [« Has difficulty organizing tasks and activities » ] and Question 7 on STABILITY and STD\_RT [« Does not follow through on instructions and fails to finish work » ]. We found no significant effect for the four remaining questions, which were less directly related to the specifics of BLAST (as BLAST involves very clear task instructions, a short duration and a quiet environment): « Is easily distracted by outside stimuli » ; « is forgetful in daily activities » ; « does not seem to listen when spoken to directly » ; « Loses things necessary for his tasks or activities » .

The same analysis of hyperactivity questions led to significant results for one question only [« interrupts or is intrusive » ]: STABILITY and PCTERRORS, KW,  $p < 0.01$ ). Overall, our analysis indicates that BLAST is almost uniquely sensitive to the Inattention component of the ADHD rating scale, and more precisely with the observed inability to stay-on-task.

## BLAST scores and participants' daily conditions and occupations

Using the same approach as above, we tested for a possible effect on BLAST of several important elements of children's life, including the socio-professional category of their parents (mother/father, separately) and extra-curricular activities (time spent watching TV or video-gaming, practicing sport or artistic activities). We found no significant effect on any of the BLAST indices (normalized by age). We also tested whether performance was affected by the time of day at which BLAST was performed (early or late morning, early or late afternoon), but found no significant effect on any of the BLAST measures.

Visualization of the effect of age and sex on the global, inattention and hyperactivity scores.

< supplementary figure 1 about here >

Visualization of the effect of age and sex on the Error Percentage, on MEDIAN\_RT and on STABILITY.

< supplementary figure 2 about here >

Models of Age-stratified normative data

< supplementary figure 3 about here >

## Adaptive versions of BLAST

The adaptive versions of BLAST measured the participants' fastest reaction time under an accuracy constraint (five consecutive successful trials, see methods). Unsurprisingly, we found that such reaction time limit was longer for more complex tasks. The median reaction time (for correct trials) increased from S-BLAST to C-BLAST, BLAST and 8-BLAST (see Supplementary Fig. 2): S-BLAST (MEDIAN\_RT\_CORRECT, mean = 300 ms +/- 60 ms); C-BLAST (mean = 390 ms +/- 90 ms); BLAST (mean = 538 ms +/- 105 ms); 8-BLAST (mean = 687 ms +/- 148 ms). The cost of increasing complexity was higher for younger participants but on average, the cost of increasing search difficulty - from four to eight items - and the benefit of removing the search component - from four items to one item - were roughly equivalent to 150 ms (BLAST to 8-BLAST, + 149 ms; BLAST to C-BLAST, -148 ms). The cost of converting the abstract answer (yes or no) into a motor response (S-BLAST to C-BLAST) was 90 ms (supplementary figure 4).

< supplementary figure 4 about here >

## iEEG study : supplementary figures

< supplementary figure 5 about here >

< supplementary figure 6 about here >

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## Supplementary figures legends

Supplementary Figure 1 : Distributions of Inattention, Hyperactivity and global scores of the ADHD rating scale as a function of age (8-11 y-old, 11-15, 15-18) and sex (geom\_violin graph, ggplot2 library, R). SCHOOL database.

Supplementary Figure 2 : Distribution of MEDIAN Reaction Time, STABILITY and the Error Percentage as a function of age and gender (pink = F; blue = M) (MUSEUM database).

Supplementary Figure 3 : Models of Age-stratified normative data for the main behavioral indices quantifying the ability to stay on task in BLAST. Third-order Polynomial best-fits of the distributions.

Supplementary Figure 4 : Median reaction time for each of the adaptive versions of BLAST.

Supplementary Figure 5 : Example of individual response in the left ITG during BLAST. a) Exact location of the recording site reconstructed onto the patient's individual 3D MRI. b) HFA increase during BLAST (blue), C-BLAST (red) and S-BLAST (black) expressed in % of the average HFA across the entire experiment for that site. Horizontal lines indicate time windows with a significant deviation relative to the pre-stimulus baseline level in each condition separately (same color code as above). Pink



horizontal lines indicate time windows with a significant difference between the two conditions in the graph (FDR corrected). c) HFA increase induced by flashed pictures of different categories (object, pseudo-words and consonant strings) during a visual oddball task performed by the patient in a separate session (see Kuzovkin et al. 2018 for a detailed presentation of the protocol). Picture onset is at 0 ms, and each horizontal line corresponds to one single picture. The matrix illustrates the specificity of the visual response to letter strings, for that site (MNI coordinates, -66 -49 -17). Kuzovkin I, Vicente R, Petton M, Lachaux J-P, Baciú M, Kahane P, et al. Activations of deep convolutional neural networks are aligned with gamma band activity of human visual cortex. *Commun Biol.* 2018;1(1):107.

Supplementary Figure 6 : Example of individual responses in the left Dorso-Lateral PreFrontal Cortex (DLPFC) and left ventral PreMotor Cortex (vPMC) during BLAST. Same legend as the previous figure. Response to the Array in the left DLPFC (top) was especially strong in the BLAST condition. MNI coordinates for this site were [-50 26 24]. Response in the left vPMC (bottom) was especially strong to the Target in the BLAST condition. MNI coordinates for this site were [-49 -1 21].

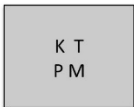
Supplementary Figure 7 : Examples of individual responses in the right frontal and parietal cortex. Same legend as above. Responses were especially strong to the Target in the BLAST condition for all sites. MNI coordinates: in right Frontal Operculum [50 21 4], right DLPFC [50 33 14], right precentral sulcus [54 1 34], right pre-SMA [11 10 48] and right IPS [29 -58 44].

Supplementary Figure 8 : Examples of local deactivations induced by BLAST. Same legend as before. The deactivation was especially strong to the Array in the BLAST conditions for sites in the right MTC (MNI coordinate [57 -31 -3]) and left TPJ (MNI coordinate [-54 -51 36]). The deactivation was especially strong to the Array in the BLAST condition in right OFC (MNI coordinate [49 27 -12]), right vmPFC (MNI coordinate [7 27 -26]) and right PCC (MNI coordinate [11 -46 29]).

	<b>Sustained between target and array</b>	<b>Sustained between array and motor response</b>	<b>Time-locked to motor response</b>
S-BLAST	none	none	Motor output
C-BLAST	none	Easy Visual search (pop-out)	Conversion between yes/no response + motor output
BLAST	Encoding/maintenance of target into working memory	Difficult Visual search (4 items)	Conversion between yes/no response + motor output
8-BLAST	Encoding/maintenance of target into working memory	Difficult Visual search (8 items)	Conversion between yes/no response + motor output

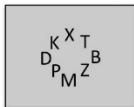
**Supplementary Table 1 :** hypothesized sequence of cognitive operations required by each version of BLAST, for each phase of a trial. For instance, in BLAST, we expect neural populations supporting letter encoding and maintenance into working memory to be active in a sustained fashion in the time window between target presentation and array display. C-Blast and S-Blast do not require such processes. In the third column, the “conversion” refers to the selection of the correct manual response (left or right) associated with the yes/no answer. S-Blast does not require that conversion. “Motor output” refers to the preparation and execution of the finger movement.

BLAST



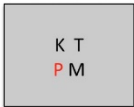
no      yes

8-BLAST



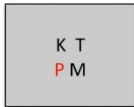
no      yes

C-BLAST

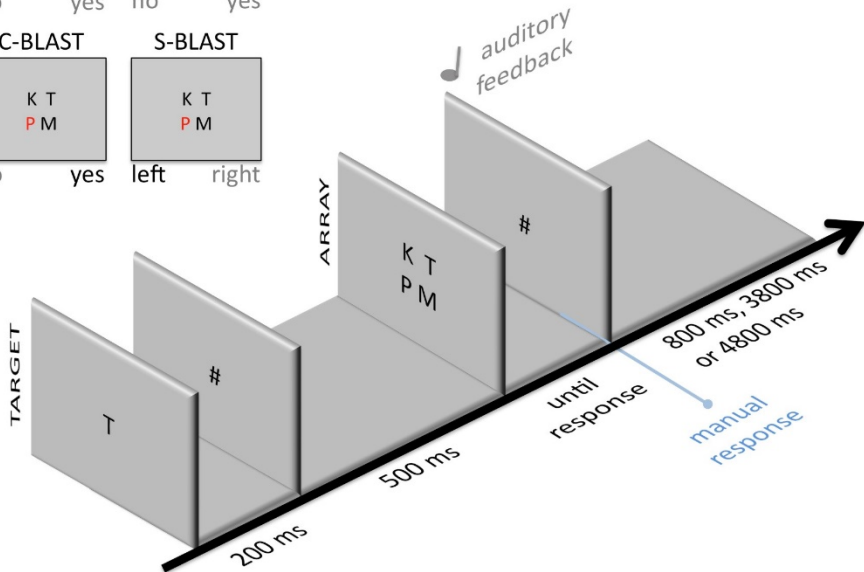


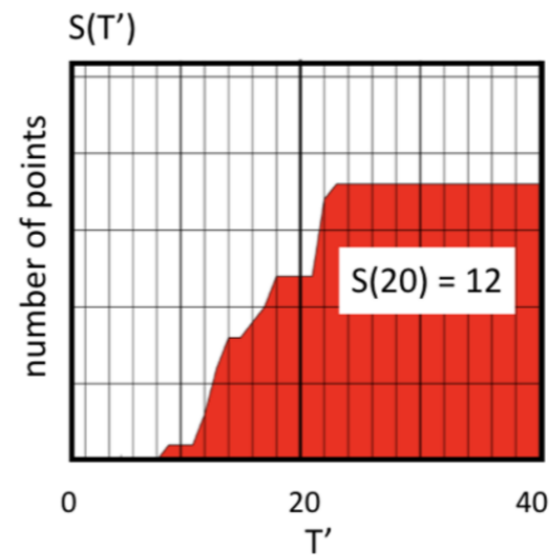
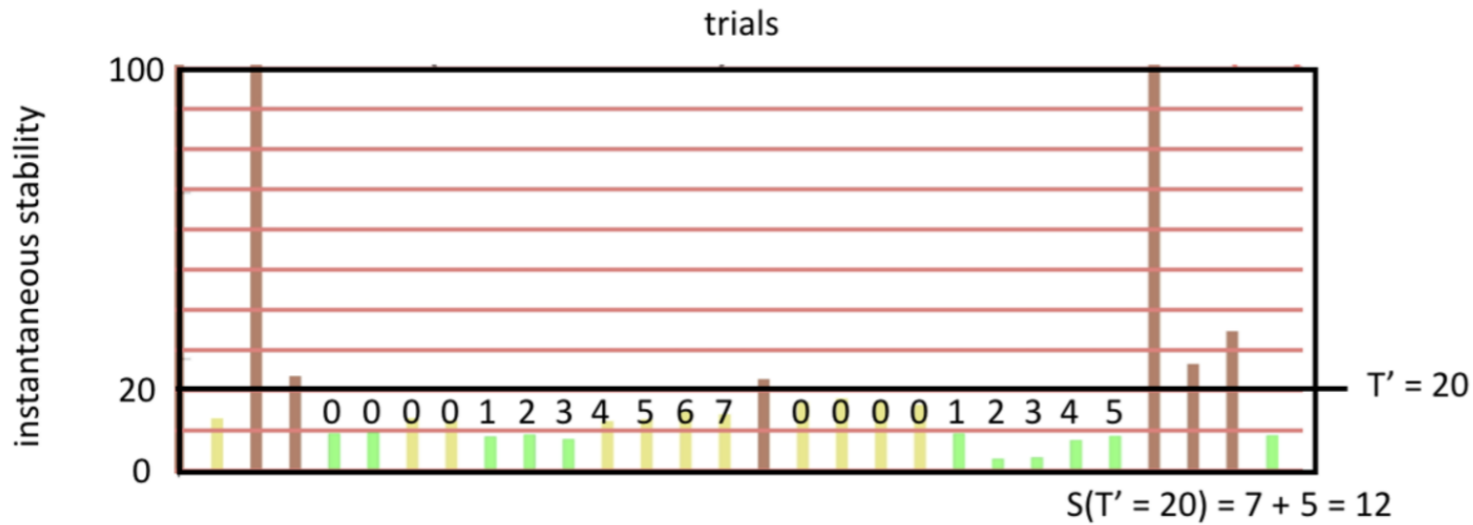
no      yes

S-BLAST

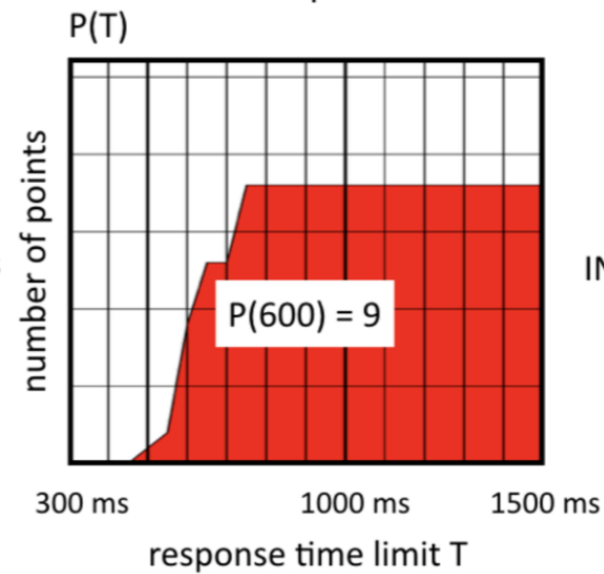
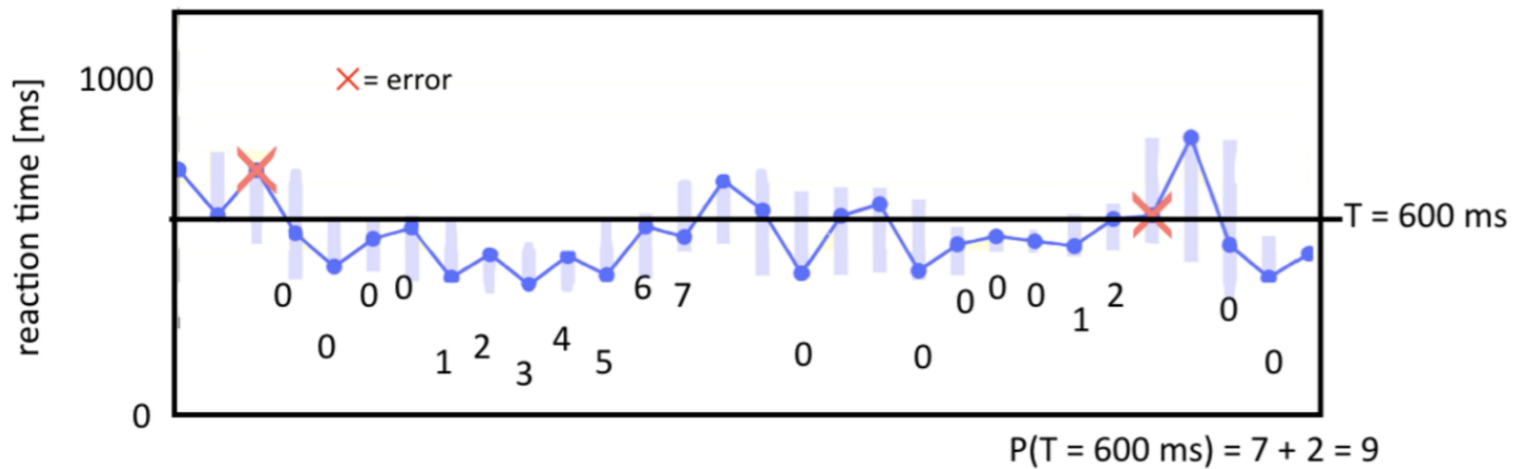


left    right

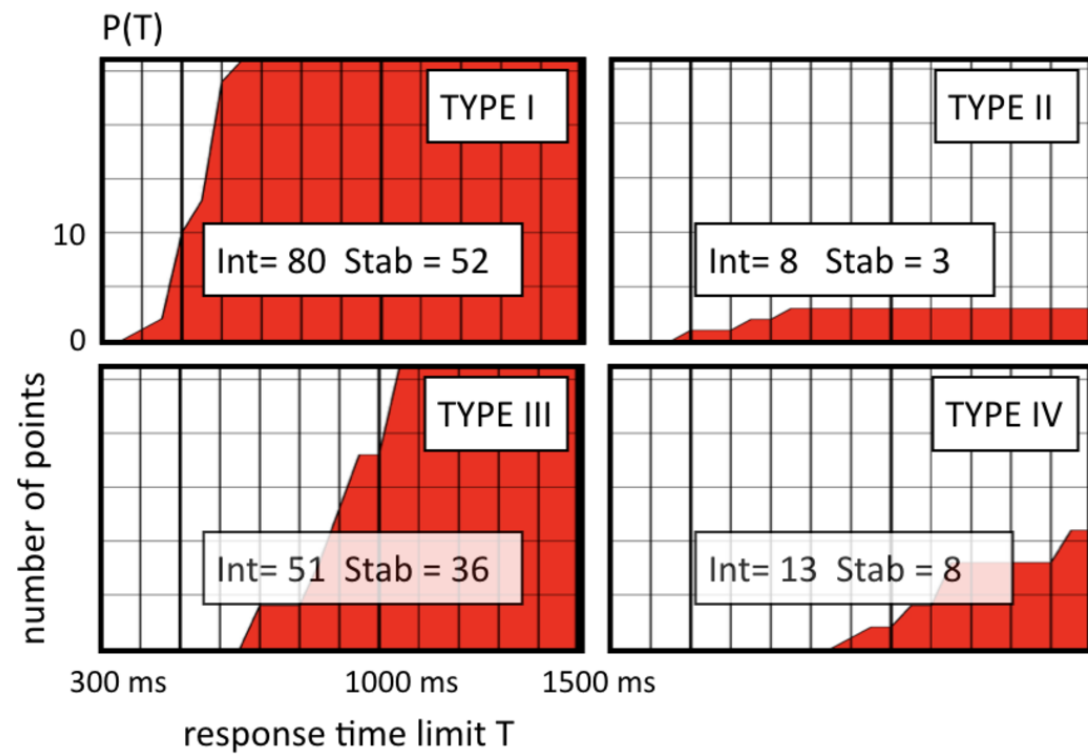
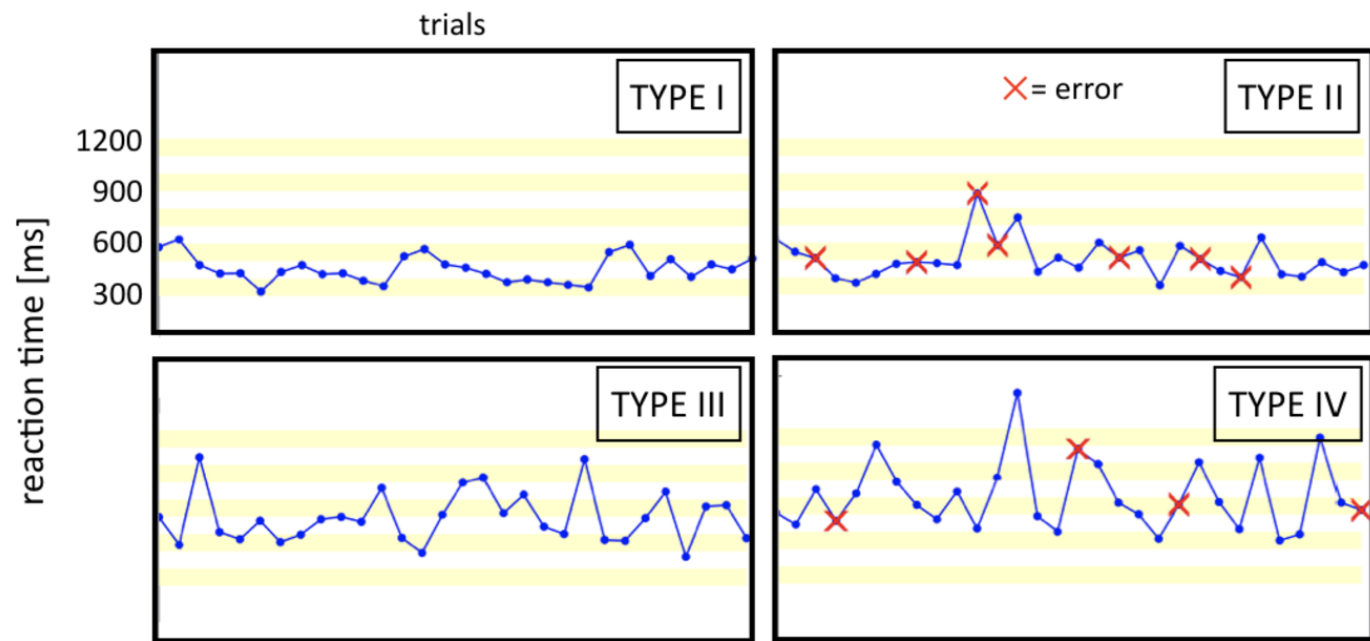


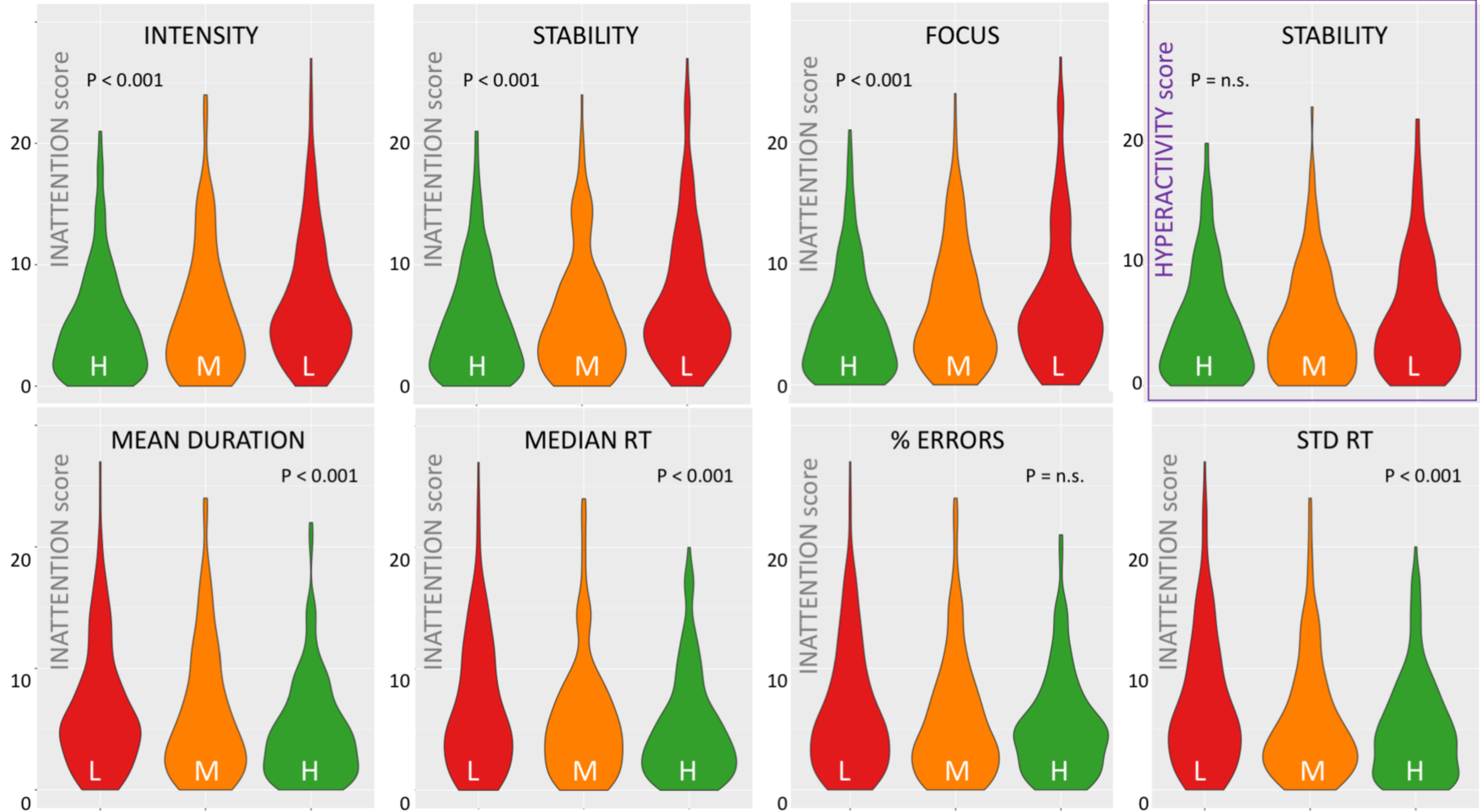


STABILITY =  $\frac{\text{[Area under curve up to } T']}{\text{[Total Area]}} \times 100$



INTENSITY =  $\frac{\text{[Area under curve up to } T]}{\text{[Total Area]}} \times 100$



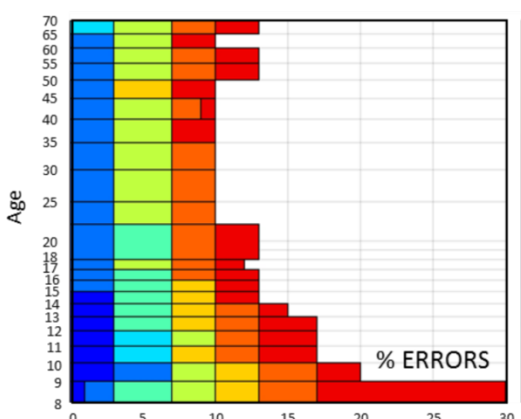
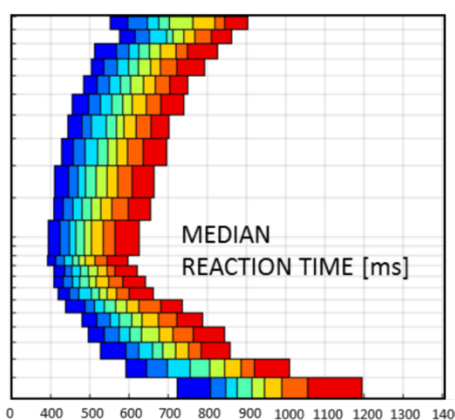
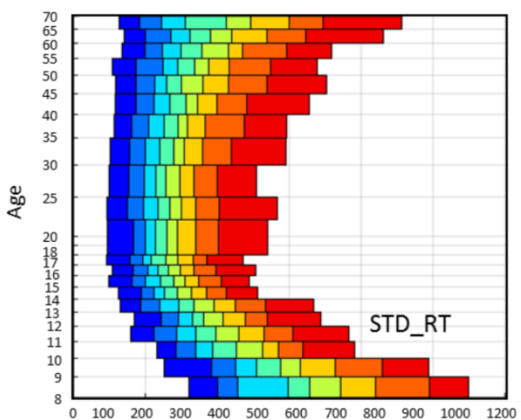
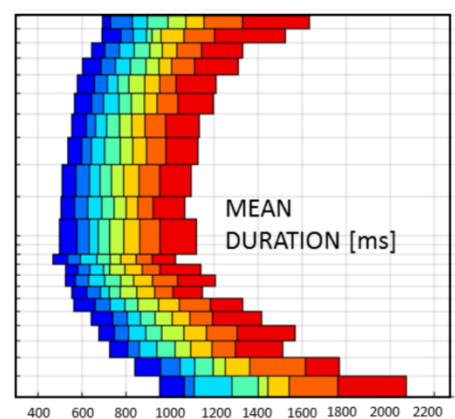
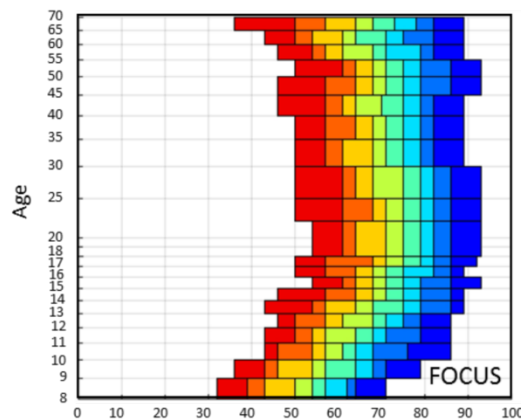
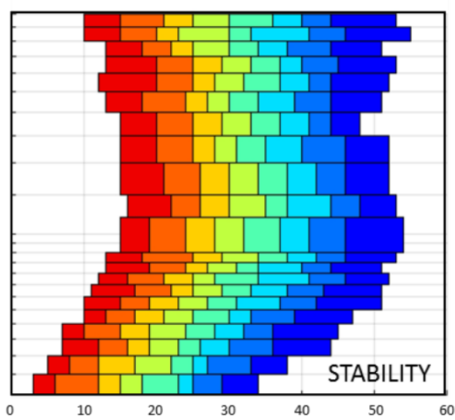
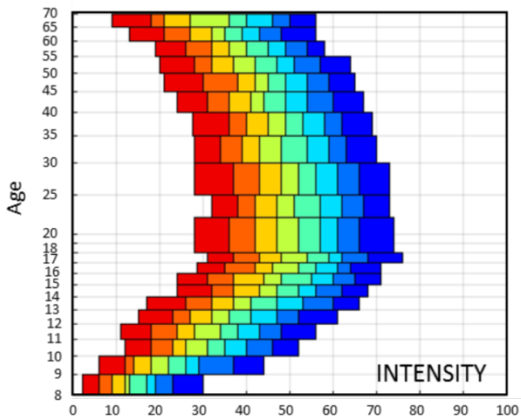


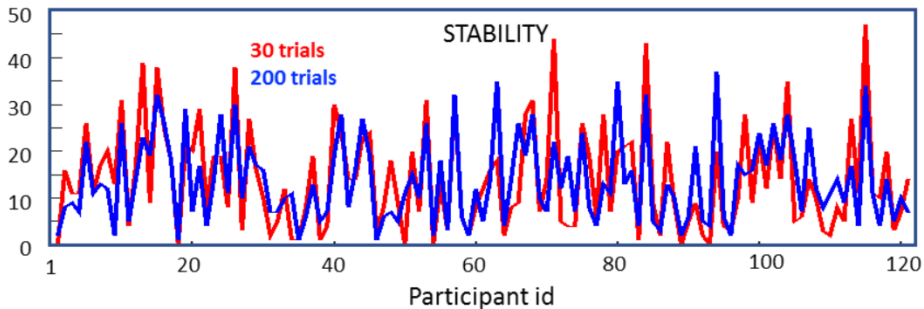
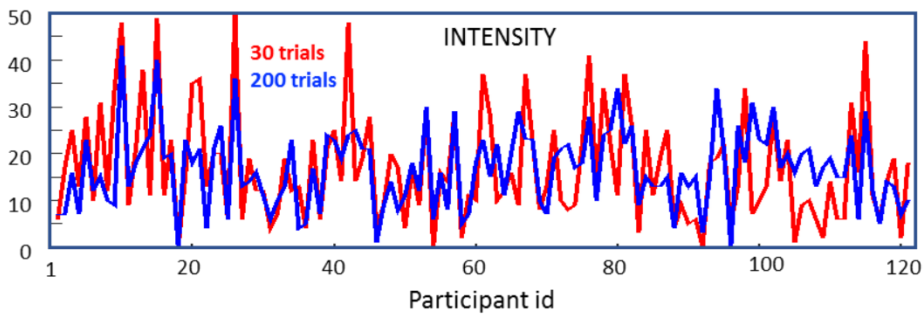
FOR EACH INDICE :

■ HIGH 33%

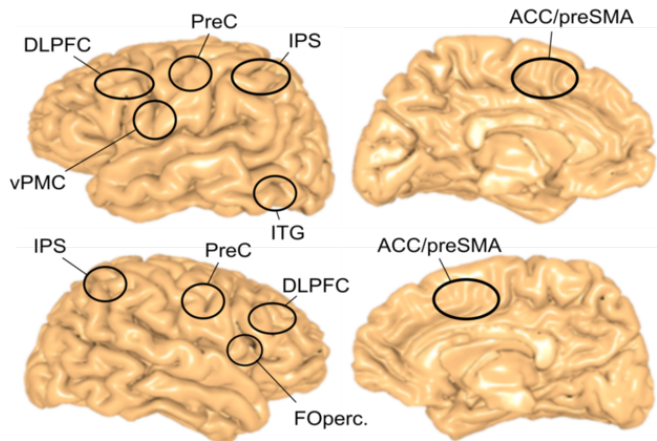
■ MID 33%

■ LOW 33%

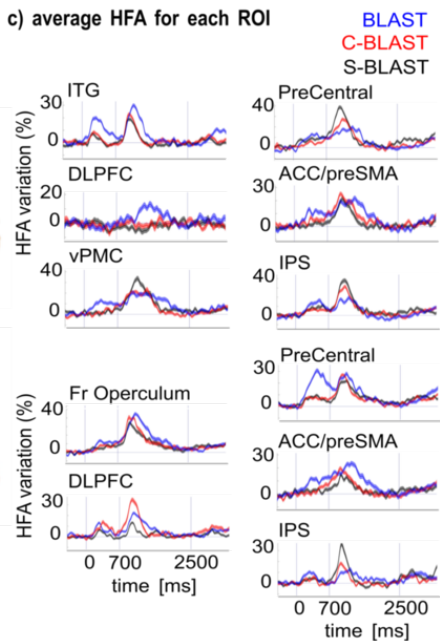




a) task-induced HFA increases



c) average HFA for each ROI



b) task-induced HFA decreases

