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The relationship between critical flicker fusion threshold and executive function across the autistic trait spectrum

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Sam Stuart Cowling, BSc (Hons), Psychology with Clinical Psychology

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Supervised by Dr. David Smith and Prof. Kevin Riggs

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Abstract

Previous research by Mewborn *et al.* (2015) investigating the link between Critical Flicker Fusion Threshold (CFFT) and higher-order cognitive functions found a significant correlation between CFFT and executive function, as measured by scores from the Shifting Attention Task. Given the well-established links between autism and deficits in executive function, and the less well-established links between autism and flicker perception, this study explores the possible link between CFFT, executive function, and autistic traits. Using an achromatic flicker task, no relationship was found between CFFT and executive function and CFFT and self-rated autistic traits (as measured by the Autism Quotient; Baron-Cohen *et al.,* 2019). This investigation also found no relationship between CFFT and processing speed (as measured by the processing speed index from the WAIS-IV; Wechsler, 2008), but the current study did find that processing speed significantly predicted executive function. These results cast some doubt on the notion that CFFT, a proxy measure of processing speed is related to executive function and that flicker perception is related to autistic traits. Further questions and additional research and theoretical ideas are developed, along with possible explanations for these, and previous findings.

The relationship between Critical Flicker Fusion Threshold and executive function across the Autism Spectrum Quotient

Introduction

Autism is a developmental disorder with an estimated prevalence rate of between 3.0 to 11.6 per 1000 in Europe (Chiarotti & Venerosi, 2020). Amongst its many symptoms are restrictive and repeated patterns of behaviour which can be manifested by rigidity in routines and interests, impaired social and emotional reciprocity, difficulty communicating verbally and nonverbally, which is sometimes evident in the individual's difficulty in understanding and maintaining human relationships and in behaving in a multitude of social contexts (American Psychiatric Association, 2013).

Multiple studies and reviews show that there are deficits in executive function in autism (Craig *et al.,* 2016; Ozonoff, *et al.*, 1991; Russell, 1997). Executive functions refer to a number of mental skills including inhibitory control, working memory, cognitive flexibility, reasoning, problem solving and planning. Executive function has been shown to be predictive of multiple aspects of people's lives, including physical health (such as diet and substance abuse; Miller *et al.,* 2011), academic success (Duncan *et al.,* 2007), marital success (Eakin *et al.,* 2004) and social problems (such as regulating anger and delinquency; Denson *et al.,* 2011). In recent years, several studies have looked at flicker performance (the ability to tell whether a light is flickering on and off versus being constantly on) within autism but with inconclusive results. Some studies show no difference in flicker performance between groups with autism compared to control groups without (Bertone *et al.,* 2005; Pellicano *et al.,* 2005) while some evidence has shown that low-autistic groups have enhanced (achromatic) flicker perception in comparison to high-autistic groups (Thompson *et al.,* 2015) meaning that the high-autistic groups have diminished ability in distinguishing between a light source which is flickering on-and-off and a steady light. Mewborn *et al.* (2015) reported a link between flicker rates and executive function within neurotypical groups – higher flicker rates were associated with better performance on an executive task independent of age or cognitive ability. The point of this study is to explore the relationship between flicker rates and executive function as a function of scores on the autism spectrum quotient (Baron-Cohen *et al.,* 2001), while also investigating whether processing speed, as measured by the processing speed index of the WAIS-IV (Wechsler Adult Intelligence Scale; Wechsler, 2008) has a relationship with CFFT.

Critical Flicker Fusion Threshold

The Critical Flicker Fusion Threshold (CFFT) is a temporal measure of visual processing performance and is the rate at which a flickering stimulus, such as a light turning on-and-off repeatedly over time, becomes indistinguishable from a steady light source. The CFFT is held as a proxy measure of visual processing speed and capacity, and is reliant on processing by the eye and the brain (Curran *et al.,* 2004; Landis, 1954; Mewborn *et al.,* 2015). Salthouse (1996a) argues that in the same way that higher processing speed in a computer allows more operations over time and thus speeds up time to task completion, in an admittedly rather crude analogy, then processing speed (of which CFFT is a proxy) is linked to performance in a number of cognitive functions (Mewborn *et al.,* 2015). This applies not only to such cognitive functions as episodic and working memory (Salthouse, 1996a, 1996b), but also to higher cognitive domains, such as executive function and volitional tasks variously characterised as planning, organisation, self-regulation and the initiation of actions.

Salthouse's Processing Speed Theory

According to Salthouse's (1996a, 1996b) processing speed theory, age-related slowing of processing speed in the brain leads to a deterioration of functions including memory, reasoning and spatial abilities. This theory attributes the slowing of processing speed to a limited time mechanism in which processing deficits are caused by a significant amount of time being devoted to early operations. In tasks requiring low cognitive load which would be completed fully accurately if there was no time limit, the diminished performance can be explained as insufficient time being given for the individual to operate vital functions. Cognitively young brains (analogous to computers with higher clock speeds) move through the operational steps of a cognitive process faster improving cognitive function. This should, theoretically mean that a person with a fast brain processing speed can undertake cognitive tasks more efficiently than an individual with a slower processing speed, and that a reliable measure of processing would show this relationship, when a suitable cognitive test is given.

Salthouse (1996a) also explains an alternative mechanism, known as the simultaneity mechanism, in which diminished performance is explained by loss of the products of early processing before late processing occurs. Information is lost or degraded over time, making it difficult for the individual to complete cognitive functions including encoding, elaboration, searching, retrievals, rehearsals, integration and abstraction. This occurs in more difficult tasks in which the individual is required to work with multiple pieces of information simultaneously, such as in tasks of working memory. This mechanism is illustrated to being like juggling, since complex tasks require rapid processing speed to synchronise information to ensure that the performance is not degraded. Examples of when these age-related deficits in processing speed due are observed are when elderly participants perform tasks which require processing speed such as the Digit Symbol Substitution Test (DSST; Wechsler, 1939), visual matching and cross out tests or in visual search tasks (Woodcock & Johnson, 1990). In adults, there is a negative correlation between age and number of items completed (Kail & Salthouse, 1996; Salthouse, 1993).

There are three main features of the processing speed theory of cognitive aging. First, there is a capacity which is limited in quantity which increases into early adulthood and then decreases in late adulthood. Second, performance on processing tasks improves when the capacity is increased, making more cognitive resources available. Third, this construct is said to be global in the sense that increased mental capacity is required for a wide variety of processes. In the case of working memory, for instance, there is a limited capacity which can be refreshed and is influenced by time available and this may affect the quality of task performance. This means that an individual with poor working memory may display diminished performance when completing a task reliant on this skill due to the lack of capacity and time available to complete operations (Salthouse 1996a, 1996b).

Salthouse (1996a, 1996b) argues that speed of processing is a general underlying factor that can explain individual differences in intelligence, not just age-related differences in cognitive ageing. Speed of processing is taken to be the single most important component in the general intelligence *g* factor which contributes to underlying specific abilities such as memory, reasoning, fluency and knowledge (Deary, 2001). Researchers have attempted to measure mental speed in a number of ways; traditionally one of the most popular methods is by using speeded psychometric tasks such as the ‘digit-symbol substitution test (DSST; Wechsler, 1939). Other measures have used reaction times in inspection tasks – asking participants to respond to brief usually visual stimuli (for a review see Deary & Stough, 1996). Of direct relevance to the present study has been work looking at visual processing speed function where moderate associations have been found between performance in early-stage visual processing and scores in intelligence tests (Deary, 2001; Sternberg, 2000).

The fourth version of the Wechsler Adult Intelligence Scale (WAIS-IV; Wechsler, 2008) is a well-known measure of intelligence which is composed of multiple subtests. The WAIS-IV provides three subtests of processing speed, which together make up the processing speed index. These subtests are designed to measure the individual’s capacity to perceive and scan visual stimuli, attend to visual material, and organise visual information, all within a limited amount of time. Hand-eye coordination is also a required in this context, and the individual is required to work quickly, completing as many items as possible.

Tests of reaction time are another method in which pioneers have attempted to measure processing speed. In experiments requiring participants to press buttons as soon as the button flashes, it was observed that reaction times are a component of intelligence (Jensen & Munro, 1979). There was a negative correlation between reaction times and intelligence, meaning that participants who responded the fastest to the lights scored higher on the intelligence tests than those who responded slower. The same general pattern of a moderate association between intelligence and reaction times has also been observed in later research with various methods of testing reaction times and intelligence, using both neurotypical and cognitively impaired populations (Deary *et al.,* 2001; Der & Deary, 2017; Neubauer, 1990). Another method of measuring brain processing speed by proxy is measuring the critical flicker fusion threshold (CFFT) – and this is of especial relevance to the present study.

Measuring CFFT

While there are several methods of measuring CFFT. An evaluation of the three main methods of measuring CFFT was undertaken by Eisen-Enosh *et al.* (2017) who looked at the method of limits, method of constant stimuli, and the staircase method. They used a custom-built system where a small LED bulb was turned off and on repeatedly.

The method of limits involves changing the flicker rate over time either by increasing or decreasing the flicker rate until the participant reports the light as having changed (either to have become steadily lit or flickering depending on whether the rate was being increased or decreased respectively). Eisen-Enosh *et al.* (2017) demonstrated this by using ascending and descending trials. The ascending trials started at 20 Hz (an LED bulb turned on and off 20 times in a second, a rate at which most humans can perceive flicker while looking directly at the stimulus (see: de Lange, 1958; Seitz *et al.,* 2006) and gradually increased in frequency until the participant reported that the LED appeared to not be flickering (steadily lit). Descending trials started at 60 Hz (a rate above which humans can process flicker (Curran *et al.,* 2004; Mewborn *et al.,* 2015; Setiz *et al.,* 2006; Thompson *et al.,* 2015; Viyana-Estopa *et al.,* 2004) and reduced in frequency until the participant reported that the LED appeared to be flickering. The threshold was calculated as the mean of three ascending trials and three descending trials.

For the method of constant stimuli task, 20 repetitions of a predetermined number of different flicker rates (the lowest rate being 10 Hz below the participant’s method of limits CFFT average and the highest being 10 Hz above this) were presented in a randomised order, and participants were required to choose which of two LEDs was flickering. In each trial one LED flickered at the given rate and the other LED was the ‘steady’ light (flickering at 120Hz, significantly too high to perceive flicker at the stimulus’ size of 0.2 degrees of visual angle; see: de Lange, 1958) in a two-alternative forced choice procedure (2AFC). A sigmoid curve was fitted to the data and the mean CFFT of the participant was chosen as the 80% point on this curve (Eisen-Enosh *et al.,* 2017).

Alternatively, there is also a staircase method of measuring CFFT which involves a 2AFC paradigm where one of two stimulus lights could either by flickering or steady. The stimulus flicker rate is increased when the participant is correct (across a set number of trials) and decreased when they are incorrect. Participants continue the task until a set number of reversals (incorrect followed by correct responses or *vice versa*) has been reached, thus converging on a specific percentage of correct responses to calculate a mean threshold. Participants were required to correctly judge which LED was flickering for three consecutive trials for the frequency to increase in the subsequent trial. When an incorrect response was made, the flicker rate was reduced in the subsequent trial. The staircase used in this instance was three-up-one-down, with a step size of 2Hz. The task was ended after eight reversals and the mean of the final six reversals was used for calculating the threshold.

There was no significant difference in mean CFFT between the three methods though the method of constant stimuli method required the most time to test and the method of limits was the quickest. Eisen-Enosh *et al.* (2017) reported that the method of limits is prone to subject bias. Such findings for flicker perception agree with standard findings in psychophysics (Boff *et al.*, 1986; Simonson,1952; Zhou *et al.,* 2016).

Stimuli for CFFT tasks can be presented achromatically, monochromatically or as a colour-fusion. The visual stimulus for an achromatic flicker task can be a singular neutral coloured white or grey bulb, whereas the stimulus for a monochromatic flicker task can be a bulb of any non-neutral colour such as red, green, yellow or blue (Eisen-Enosh *et al.,* 2017; Landis, 1954). Colour-fusion flicker tasks involve presenting flickers of two alternating colours. For example, Brown *et al.* (2013) used both blue/yellow and red/green colour fusion tasks as their chosen methods of presenting colour fusion stimuli. All types of chromatic flickers are processed in the lateral geniculate nucleus. Achromatic flicker perception has been shown to be reliant on magnocellular functioning (Peters *et al.,* 2020), as is the case with monochromatic flicker perception (Zhuang *et al.,* 2015). The type of visual pathways used for colour fusion flicker tasks depend on the colours being presented. For instance, in the viewing of red/green flicker stimuli, evidence has shown that the parvocellular regions of the lateral geniculate nucleus are active (Masri *et al.,* 2020), whereas for any stimulus alternating between yellow and blue, the koniocellular pathways are activated (Pietersen *et al.,* 2014).

Critical Flicker Fusion Threshold and Intelligence

Halstead (1947) made the distinction between biological-based and psychometric-based theories of intelligence. It was argued that one of the dozens of operationalised biological markers for intelligence he argued for was critical flicker fusion rate. Halstead (1947) proposed that CFFT is driven predominantly by processes within the cortex. A review of available data showed that CFFT's in neurologically-healthy participants differed compared to participants with damage in any of the four lobes of the brain. Participants with frontal lobe brain damage generally had the lowest thresholds. For this reason, Halstead (1947) argued that intelligence is influenced by all four lobes equally, but that lesions to the frontal lobes are the most crucial factor in determining level of impairment. A strong correlation was observed between CFFT and four measures of intelligence including central integrative (the ability to process familiar information), abstraction, power and direction. These were the measures of intelligence which Halstead (1947) coined as a “biological intelligence”.

The idea that higher flicker rates should correlate positively with higher intelligence test scores has been tested by a number of researchers with mixed results. Early work by Tanner (1950) and Colgan (1954) showing significant positive correlations between flicker and intelligence have been questioned because no possible mechanism could be seen whereby, they could be linked (Landis & Hamwi, 1956). Nevertheless, there have been a number of studies reporting small to medium correlations between flicker and various measures of intelligence (Cautela and Barlow, 1965; Zlody, 1965). There is some concern that though CFFT might be objectively measurable, there are a number of different versions of intelligence with which to correlate it; Barratt *et al.* (1962) reported a non-significant correlation between flicker and the Wechsler Intelligence Scale for Children, a significant negative correlation with the Otis IQ, and a significant positive correlation with the Cattell Culture Fair Intelligence Scale (see Jensen, 1983). A sophisticated early attempt at measuring CFFT using a red LED where the flicker rate was controlled by the participant via the turning of a rheostat (hence a method of adjustment) reported a slight correlation between CFFT and verbal (Concept Mastery Test) and nonverbal intelligence (Raven’s Advanced Progressive Matrices) though the author rejected the usefulness of the measure as he was unable to see how a connection could be made between information processing, intelligence and speed of processing of visual change (Jensen, 1983). It might be too much to expect a direct general link between CFFT and intelligence. Nonetheless, there might be a mechanism to link speed of processing with certain attributes of intelligence which would directly tie in CFFT with decision-making as shown in executive function tasks.

Critical Flicker Fusion Threshold and Executive Function

Recently, Mewborn *et al.* (2015) investigated the relationship between CFFT, global cognition, and various cognitive subdomains and its relation to age-related changes in cognitive decline as measured by the CNS Vital Signs Battery (Gualtieri & Johnson, 2006). The CNS test battery includes tasks such as a shape learning task for visual memory, a word list remembering task for verbal memory, finger tapping and Stroop tests for reaction time, and a symbol digit coding task for measuring processing speed. Mewborn *et al.* (2015) found a positive correlation between CFFT and executive function as measured by scores on Shifting Attention Task (SAT), when the CFFT was measured by the method of limits, with a 660 nm (red) LED bulb used as the visual stimulus.

The Shifting Attention Task measures the set shifting, updating, and inhibition components of executive function (Gualtieri & Johnson, 2006). In this task, participants are presented with a prompt shape (either square or circle) that is coloured (either red or blue) and the participant is required to apply either a shape or a colour-matching rule (where which rule to apply changes randomly from trial to trial) to match the prompt stimulus to one of two other candidate stimuli presented (see fig 4, page 25 for a schematic of this test).

The only significant interaction, as measured by a multiple regression analysis was between the CFFT and executive function. This was observed in both young and old adults – all other subtests of the CNS test battery were not significant predictors of CFFT in the multiple regression analysis, but were significant according to zero-order correlations. Participants with a higher CFFT (indicating a *faster* flicker rate before fusion) generally performed better on the SAT than those with a lower CFFT independently of their age. Age also correlated with performance on all domains of global condition with the exception of visual memory – there was an inverse relationship between age and performance on the cognitive tasks which fits Salthouse's (1996a) processing speed theory. The relationship between CFF and executive function could be observed across age groups, similar to how there has been a relationship between visual processing and higher-order cognitive function in other studies (Albinet *et al., 2012;* Lindenberger & Baltes, 1994; Saint *et al.,* 2019) whereas the relationship between CFFT and executive function was explained by the reasoning that high visual processing speed is important for carrying out executive functions. Furthermore, Mewborn *et al.* (2015) highlighted that fast visual processing requires neural integrity in the visual pathway, with CFFT being a measure of this and neural firing rate, also highlighting that clinical populations with lesions and brain damage do worse on tests of executive function and have diminished thresholds. However, the relationship between processing speed (from the CNS vital signs test battery) and CFFT was less clear. There was a moderate positive and significant correlation, but no significant relationship in the multiple regression analysis. Since CFFT is a measure of visual temporal processing speed, and that processing speed indexes measure the ability to undertake many operations in a limited space of time, it would made logical sense for there to be a relationship between visual perception and processing speed. Nonetheless, this unclear relationship found in Mewborn *et al's.* (2015) study leaves room for further investigation.

Critical Flicker Fusion Threshold and Higher Cognitive Functions

Further evidence that visual processing speed is related to higher cognitive functions has been demonstrated by Saint *et al.* (2019) in an experiment involving pre-adolescent children between seven and thirteen years old. Visual processing speed was measured by CFFT and psychomotor reaction time with Woodcock-Johnson III Tests of cognitive abilities were used as the measures of cognitive function. Composite scores for cognitive function were calculated from tasks which assessed Brief Intellectual Ability, verbal ability, cognitive efficiency, processing speed and executive processing. A method of limits measurement for the CFFT task was used, and the visual stimulus was a red LED bulb. After controlling for the effects of age, there was a small to moderate positive correlation between CFFT and cognitive efficiency, executive function task performance and processing speed. Furthermore, faster response times on the psychomotor test were related to improved cognitive test performance in participants in comparison to participants with longer response times. This means that these participants were able to process the information faster and more accurately than those with slower response times. There were negative correlations between variable position reaction time on the psychomotor test and CFFT, and CFFT and fixed position reaction time (albeit with a smaller main effect). These findings suggest that visual processing speed is related to a number of cognitive functions and that CFFT is related to performance on tests reliant on higher cognitive functions. These findings are similar to the observations by Deary *et al.* (2001) and Der and Deary (2017) in that these results show that processing speed is related to cognitive function (although Saint *et al.,* 2019 showed this using CFFT- a proxy measure of processing speed). Therefore, these findings also offer support for Salthouse's (1996a) notion of a limited time mechanism in which a person with an efficient brain can perform an increased number of operations and *vice versa*.

Executive Function in Autism

Multiple studies and reviews show that there are deficits in executive function in autism (Ozonoff, *et al.*, 1991; Russell, 1997). Craig *et al.* (2016) reviewed deficits in executive function in autism to see how the flexibility and planning components of executive function were affected. Aspects of executive function including inhibition, working memory, attention, monitoring, planning, fluency and concept formation were reviewed. For autism, studies showed deficits in response inhibition in comparison to typically developed children (Corbett *et al.,* 2009; Happé *et al.,* 2006; Kado *et al.,* 2012; Nyden *et al.,* 1999; Semrud-Clickerman *et al.,* 2010; Sinzig *et al.,* 2014; Tsuchiya *et al.,* 2005; Xiao *et al.,* 2012;) whereas others did not (Goldberg *et al.,* 2005; Samyn *et al.,* 2014; Yang *et al.,* 2009;). Craig *et al.* (2016) attributed the lack of empirical agreement to variations in study such as sample size, age of participants, IQ and different assessment tools. Additionally, executive dysfunction in autism is characterised by, among other social and communication deficits, impairments in cognitive flexibility and planning which often manifest in perseverative errors (Hughes *et al*., 1994; Pascualvaca *et al*., 1998).

Restrictive, Repetitive Behaviours and Executive Function in Autism

One area of considerable research is how restrictive and repetitive behaviours (RRB's) in autism relate to executive functioning (Boyd *et al.,* 2011; Faja & Nelson, 2019; LeMonda *et al.,* 2012). The Diagnostic and Statistical Manual of mental Disorders (DSM-V; American Psychiatric Association, 2012) defines restrictive and repetition in behaviour and interests as a key part of the diagnostic criteria for Autism Spectrum Disorder (ASD). This may be observed in the person's methods of communication where their gestures may be overly exaggerated or their speech may be highly repetitive with the repeated use of specific words. A person with ASD may become distressed when small changes are made to their usual environment or routines; generally, they are characterised by an inflexible and impoverished ability to respond to change which might heavily implicate an impaired executive system (Faja & Nelson, 2019).

It is argued by Faja and Nelson (2019) that RRB's (restrictive and repetitive behaviours) in autism are related to diminished executive functioning, specifically, inhibition and cognitive flexibility. Autistic children aged between 7 to 11 completed a test battery which included the Stroop task (Stroop, 1935), change task (De Jong *et al.,* 1995; Geurts *et al.,* 2004), and parents' reports of executive function were taken with the use of the BRIEF cognitive inventory (Gioia *et al.,* 2000). Restrictive and repetitive behaviours were assessed with the use of the Autism Diagnosis Observation Schedule (ADOS) and the revised version of the Autism Diagnostic Interview (ADI-R). The RRB's investigated were in terms of range of interests and rigid behaviours. Parent-reported set shifting scores were linked to higher-order RRB's, and symptom severity was also a significant predictor of both set shifting and inhibition.

Visual processing, flicker and autism

There have been multiple attempts by researchers to investigate the relationship between autism, flicker and other measures of visual processing. Pellicano *et al.* (2005) investigated the role of magnocellular processing (motion) in visuospatial processing in autism. Performance on a flicker contrast sensitivity and global dot motion tasks (which both rely on processing within the motion pathway) was compared between children with Autistic Spectrum Disorder (ASD) and typically-developing children. The Children's Embedded Figures Test was also administered to establish whether there was any relationship to performance in local visual processing and the visual tasks. Overall, participants with a diagnosis of autism had higher thresholds for the global dot motion task, meaning that they required a higher percentage of the dots to be moving for them to be able to accurately detect the direction of movement. This suggests that those with autism had an impaired motion-detection system. In the flicker contrast sensitivity task a spatially-defined Gaussian blob flickered sinusoidally at 10 Hz. The task used a 2AFC, PEST procedure was used, calculating the thresholds when performance converged at the 75% accuracy. A sinusoidal, zero contrast version of the same temporal frequency was used as the control stimulus. There was no difference in flicker contrast sensitivity between the ASD and the typically-developing group of children. According to Pellicano *et al.* (2005) these findings show that low-level motion processing is relatively unaffected in ASD, because both the flicker and dot motion tasks are reliant on the motion pathway but only the global dot motion performance was affected. Additionally, it was also suggested that the lower thresholds in some of the children with ASD could be explained by factors such as differences in attention or decision making rather than impaired motion perception skills. Pellicano *et al.* (2005) also attribute the difficulties in perceiving global motion in the ASD group to a disruption between two stages of motion perception. In the early stage, V1 processes local information, whereas V5 integrates the local signals into a whole, as has been demonstrated by Britten *et al.* (1992) and Newsome & Paré (1988). This seems feasible, since there was no disruption in the local (flicker contrast sensitivity) task.

Bertone *et al.* (2005) conducted a study investigating flicker perception in people with a diagnosis of high-functioning autism. Thirteen people with high functioning autism and an age-matched control group took part in a luminance contrast flicker sensitivity task, in which both parvocellular (colour) and magnocellular (motion) functioning was measured at a pre-cortical level. For the magnocellular processing task, the flicker was presented at 6 Hz whereas for the parvocellular task the flicker was presented at 1 Hz and stimuli for both tasks were presented on a monitor. Both tasks used a 2AFC paradigm using a staircase to assess the minimum level of contrast required to detect the flicker. There were no significant differences in performance on either the colour or motion flicker tasks, which is not dissimilar to the finding in Pellicano *et al'.s* (2005) investigation.

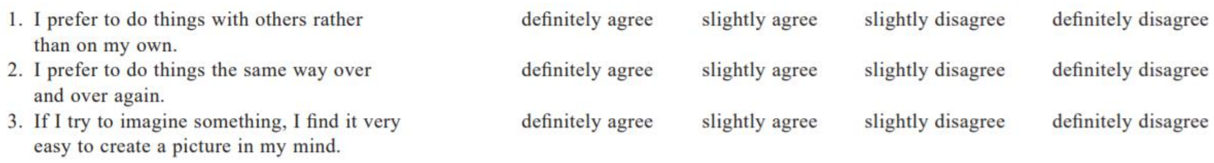
Thompson *et al.* (2015) investigated the relationship between autistic traits and CFFT. Using the Autism Spectrum Quotient (AQ) of Baron-Cohen *et al.* (2001), participants were categorised into two groups: a high AQ group (score ≥ 18) and a low AQ group (score ≤ 13). In an experiment which used a 4AFC procedure in which the stimuli for two different tasks (white LED's for the achromatic task; red/green bulbs for the colour-fusion task) were reflected onto a panel made of wood, while the participant was required to declare which stimulus was flickering. An adaptive staircase procedure was applied for both flicker tasks. The low AQ group had higher CFFT scores than the high AQ group for some of the achromatic flicker contrast levels reaching levels of statistical significance whereas there were no significant group differences in the red-green colour-fusion flicker task. This effect was only observed for the lowest achromatic contrast levels (5%, 25% and 50%). The most pronounced differences in performance were where the high-AQ CFFT was ~31 Hz and the low-AQ CFFT was ~35 Hz at the 5% contrast level. Thus, differences in CFFT between low- and high-AQ groups were small and restricted to low contrast achromatic stimuli, and the difference in performance was attributed being evidence for the notion that there is diminished magnocellular processing in people with autism. Additional evidence that achromatic flicker perception is reliant on magnocellular processing came from further work by Brown *et al.* (2018) who measured visual evoked potentials (VEPs) in autism. In this experiment, there was a high correlation between the amplitude of VEP's and high and low flicker frequencies in the magnocellular cells (in people with autism), but no correlations for responses in the parvocellular cells.

Autism Spectrum Quotient

The Autism Spectrum Quotient (AQ; Baron-Cohen *et al.,* 2001) is a questionnaire in which autistic traits can be self-rated or completed by a primary caregiver if a child's autistic traits are being measured. This can be administered to people regardless of a diagnosis of Autistic Spectrum Disorder or Asperger's Syndrome, and is often given to given to children who show signs of autism, in the absence of any learning disability (Allison *et al.,* 2012). The traits measured include attention to detail, communication and imagination. The answers are given on a four-point Likert scale (see figure 1, page 16) Originally, the AQ was used for measuring traits of autism in a clinical and general population and has been used to establish whether university students enrolled on science-based degree programs have higher levels of autistic traits than those enrolled on different types of degree (Baron-Cohen *et al.,* 2001); and has been shown to be a valid and reliable measure of autism in clinical groups, with people diagnosed with Autistic Spectrum Disorder (ASD) scoring higher on the questionnaire than people without (Broadbent *et al.,* 2013). Other researchers (Ruzich, *et al.,* 2015) have used this tool to measure autistic traits within the general population.

Figure 1

First three items from the Autism Spectrum Quotient



1. I prefer to do things with others rather than on my own.	definitely agree	slightly agree	slightly disagree	definitely disagree
2. I prefer to do things the same way over and over again.	definitely agree	slightly agree	slightly disagree	definitely disagree
3. If I try to imagine something, I find it very easy to create a picture in my mind.	definitely agree	slightly agree	slightly disagree	definitely disagree

Note: Questions from the Autism-Spectrum Quotient as they appear in the original questionnaire. From "The Autism-Spectrum Quotient (AQ): Evidence from Asperger Syndrome/High-Functioning Autism, Males and

Females, Scientists and Mathematicians" by Baron-Cohen *et al.,* (2001), *Journal of Developmental Disorders, Vol. 13,* No. 1.

Rationale

Given the strong link between autism and executive dysfunction (Craig *et al.,* 2016; Faja & Nelson, 2018; Ozonoff, *et al.,* 1991; Russell, 1997), and the less certain link between flicker thresholds and autism (Bertone *et al.,* 2005; Pellicano *et al.,* 2005; Thompson *et al.,* 2015), the plan was to investigate the relationship between CFFT and executive function (Mewborn *et al*., 2015) and to extend the investigation by attempting to also establish whether there is also a relationship between CFFT and Autistic traits. A second rationale for this study was that previous research which has examined the relationship between autism and flicker has elected to use a measure of contrast sensitivity at low flicker rate rates (for instance, 6 Hz and 1 Hz in Bertone *et al.,* 2005; 10 Hz in Pellicano *et al*., 2005) rather than use a true measure of visual processing speed as shown by the CFFT, and this previous research was accomplished using a computer screen as the display vehicle rather than a hardware solution such as that provided by a flickering light source. The complicated task in measuring CFFT using a hardware solution has theoretical and methodological implications because most computer screens cannot provide an accurate measure of flicker threshold as related to flicker perception. This is because most computer monitors have a vertical refresh rate of 60 Hz, meaning that computer monitors can only produce a square-wave flicker at 30 Hz (their maximum flicker rate) and would only be able to produce very choppy sinusoidal-flicker (quantised at approximately 32 levels) at a maximum rate of 3.75 Hz. The use of non-sinusoidal flicker introduces anomalous frequencies into the flickering stimulus which can produce temporally-aliased low-frequency artifacts which lead to catastrophic confounds in the study. This means that a computer monitor (even with ultra-high refresh rates of screens for gaming running at 480 Hz) cannot be used to reliable measure CFFT and certainly not for well-approximated sinusoidal temporally-modulated flicker. Where a CFFT has been collected using a more reliable hardware-based technique such as flickering LEDs (Thompson *et al.*, 2015) the threshold definitions of the low- and high-AQ groups (≤ 13 for low and ≥ 18 for high) mean that both groups fall within typical AQ scores in a neurotypical control sample group (Mean: 16.4, STD: 6.3 in Baron-Cohen *et al*., 2001). This has left further room for investigation into this effect.

Therefore, the present study consisted of requiring participants to take the 50-item Autism Spectrum Quotient scale (AQ; Baron-Cohen *et al*., 2001), measuring participants' CFFT using a single flickering LED using a standard staircase method, and measuring participants' performance on executive function using the SAT from the CNS vital signs (Gualtieri & Johnson, 2006). Processing speed was measured with the use of the processing speed index of the WAIS-IV (Wechsler, 2008), and the relationships between processing speed and CFFT and SAT performance and CFFT were tested in the analyses. The relationship between CFFT and Autism Spectrum Quotient was also analysed.

As with the findings in Mewborn *et al.* (2015) and Saint *et al.* (2019), CFFT was predicted to correlate negatively with reaction times on the SAT (since fast reaction times are indicative of enhanced performance), and was expected to be a reliable predictor of this. It was also expected that there would be a negative correlation between CFFT and AQ, as the study by Thompson *et al.* (2015) suggests that achromatic flicker perception is enhanced in people with low autistic traits. It was also predicted that there would be a significant relationship between processing speed (as measured by the mean z-scores across all three processing speed index tasks) and performance on the SAT, as measured by reaction times for correct trials. This study has thus attempted to link visual processing speed (CFFT) with intelligence (processing speed index of the WAIS-IV), executive function, and autism.

Method

Participants

A total of 34 participants took part in the study. Due to five data collection errors, and one participant missing items on the Autism-Spectrum Quotient (AQ) questionnaire, the data sets of six participants were excluded. The data from the remaining participants (n = 28) was used in the analysis (mean age: 20.57 years, *SD*: 2.12 years, age range: 18-25 years). All participants were students from the University of Hull and all (with the exception of one engineering student) were students from the Department of Psychology working towards a variety of undergraduate and postgraduate degrees.

Exclusion criteria included diagnosis of epilepsy, history of epilepsy in a first-degree relative, or self-reported levels of colour blindness. All participants reported normal or corrected-to-normal visual acuity (using either spectacles or contact lenses). The reimbursement for taking part was a single course credit in fulfilment of completing a research skills module.

Materials and Equipment

An Elegoo Uno™ R3 (Elegoo, 2020) microcontroller board was connected to a solderless breadboard (Farnell Inc, 2020a, length: 8.38 cm, width: 5.44 cm, 400 Tie, product number: TW-E40-510,) upon which was mounted a single Cree™ 5 mm, 12 cd/m^2, warm-white LED bulb (product number C513A-MSS-CW0Z0132; Farnell Inc, 2020b) connected in circuit with a 1 kΩ resistor. The Arduino microcontroller was connected via USB to a Windows 10 PC (screen size 34.5 cm x 19.5 cm, pixel resolution 1920 x 1080, 60 Hz vertical refresh rate). A chin rest was used to ensure participants were seated with their head positioned so that the LED was at their eye-level during the flicker task.

The linearity of the LED bulb was tested using a YF-170 (YFE) Digital Light Meter Lux/FC photometer (Manufactured by Tenmars Electronics Company Ltd) and the waveform properties of the signal were measured using a 40 Mhz Digimess MO40 oscilloscope (Serial number: 03101041). Details are provided in Appendix A.

Custom-written C structured code in the Arduino Integrated Development Environment (IDE; Arduino, 2020) controlled the luminous intensity of the LED to produce sinusoidal temporal flicker within the range of 10-100 Hz using Pulse Width Modulation (PWM)[1]. This program was loaded as a continually-looping executable onto the Arduino Uno™ microcontroller. A custom Python program (written by the researcher) was used to record and collect data, and was hosted on a Windows 10 laptop. Communication between the laptop and the Arduino Uno™ was achieved using a USB cable running from the laptop USB port to the USB-serial converter COM port on the Arduino Uno™ (see figure 2, page 20). The Arduino Uno™ was connected to an electronic circuit running from digital pin 3 (sampled at 980 Hz) to the ground pin with the 1 kΩ resistor and LED in the circuit (see figure 3, page 21). The Arduino Uno™ and breadboard were physically mounted on an adjustable tripod. Participants were seated and used a chinrest to ensure that the side of the LED bulb was at eye level.

The equation for sinusoidal change in luminance over time (sinusoidal temporal modulation) is:

$$L(t) = L_{mean} * [1 + M * sin(2\pi(F_t\, t + \theta))]$$

where $L(t)$ is the PWM value (of the LED) in time, L_{mean} is the background value [PWM value of 128 on the eight-bit scale 2^8], M is Michelson contrast [which ranges from 0 (no contrast) to 1 (full contrast)], F_t is the temporal frequency which is the number of cycles of the sinewave in a second [measured in Hz], t is time [expressed in units of the sample rate 980 Hz] and θ is the phase (the luminance level starting point of the sine wave). The LED was calibrated with

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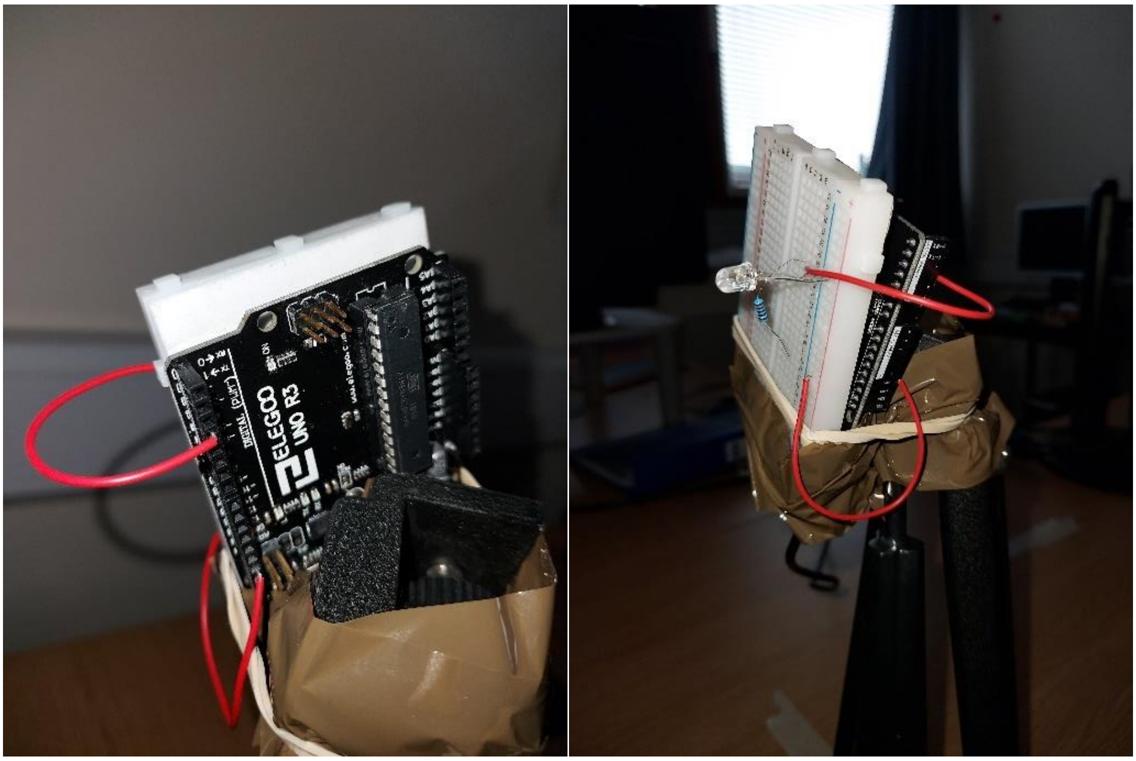
[1] PWM is a method of controlling the mean power of an electrical signal by chopping the delivery of the signal up into discrete periods of time when the signal is either on or off. This controls the power output (in this case, the brightness of the LED) and can be used to smoothly alter the duty cycle (amount of time that the LED is at full power to amount of time that the LED is off). The LED is completely off when the duty cycle is at 0% (always off, never on), at half power (half brightness) at 50% (half the time off, half the time on), and at full power (= maximum brightness) at 100% (always on, never off). Suitable proportions of time when on or off allow variation from 0 to 100% (for instance 75% is one-quarter on to three quarters of the time off).

a photometer to check linearity was maintained such that PWM value mapped linearly to luminance level in cd/m^2 (see Appendix A). The average luminance of the LED during presentation of flicker stimuli was 42.84 cd/m^2 (2.68 cd/m^2 when viewed through the 1.2ND filter).

Figure 2

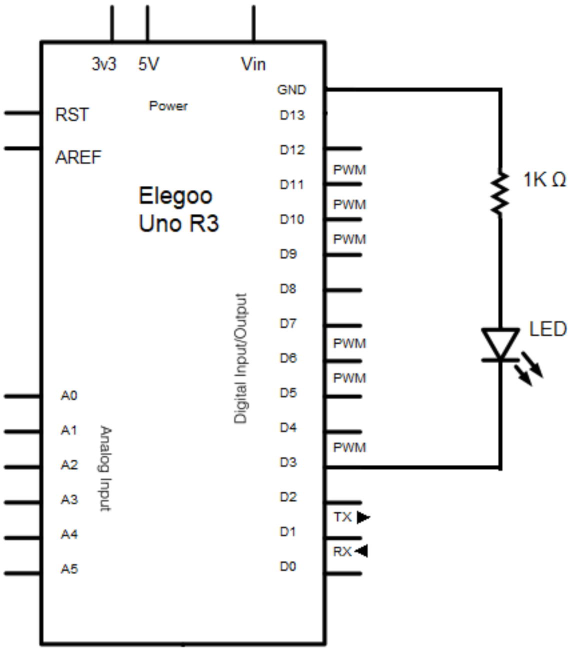
Photo of the Elegoo™ Uno R3 Board as mounted and connected in circuit with breadboard



Note: Also connected in circuit: A Cree™ 5 mm, 12 cd/m^2, warm-white LED bulb and 1 kΩ resistor. Front and back views, taken in Kingston Upon Hull, East Riding of Yorkshire, December 7th, 2020.

Figure 3

Circuit diagram of Elegoo™ Uno R3



Note: Circuit diagram is as connected to 1 kΩ resistor and Light Emitting Diode.

The adult version of the Autism-Spectrum Quotient (AQ; Baron-Cohen et al., 2001) questionnaire was administered in A4 booklet form (see appendix B).

Three subtests from the WAIS-IV were administered on paper (Wechsler, 2008). The tasks from the WAIS-IV were the cancellation and symbol search task both printed on A3 paper, and the symbol digit coding task was printed on A4 paper. Two different versions of the cancellation task are given and each are completed within a 45 second time limit. The participant is presented with rows of two different shapes, all of which are one of two different colours. A line is drawn through each target shape (i.e., a line through each red square and yellow triangle). When a row has been searched from left-to-right, the row below is then searched, starting from the leftmost shape. For the symbol search task, participants are presented with two target symbols on the left, and a search group including five additional symbols on the right, including the word “NO” inside a small rectangle. On each trial, there is either one or none of the target symbols to the right of the two targets. When a target is present, a line is drawn through it; when it is not, a line is drawn through the word “NO”. All trials are completed in order, top to bottom, starting on the left side of the page, and the participant completes the trials on the right of the page when all are complete on the left, and then moves onto the next sheet when all items have been attempted. This is completed in a time limit of 120 seconds. For the symbol digit coding task, there is a key at the top of the page consisting of geometric symbols with its corresponding number presented above each symbol. Below the key are rows of boxes of symbols (one symbol per box) separated by empty boxes which is where the corresponding symbol is written for each above number. Trials on every row are completed from left-to-right, starting from the top row, and moving to the row below when the rightmost trial has been attempted. A time limit of 120 seconds is allocated for this task. Performance on the symbol digit coding and symbol search task is measured by a score (one point for each correct trial), whereas the score for the cancellation task is measured by points for each correct target shape identified, and points deducted for each incorrect shape marked.

The Shifting Attention Task (SAT) from the computerised neurocognitive test battery CNS Vital Signs (CNSVS.com, 2020) was coded into PsychoPy3 (Peirce *et al*., 2019) and hosted on the same Windows 10 laptop which was connected to the Arduino Uno™ microcontroller.

Design

The key variables measured were AQ score, CFFT, SAT performance (as measured by mean reaction times for correct responses in milliseconds), and processing speed index, as measured by z-scores across the three subtests of the WAIS-IV (symbol digit coding, symbol search and cancellation).

While correlations were calculated between all main variables, the main correlations of interest were between CFFT and SAT performance, CFFT and AQ, and CFFT and processing speed index. Correlations between all subtests of the processing speed index were also measured, though this was not an integral part of the investigation.

Two separate standard multiple regressions were conducted. To test the notion that CFFT is related to cognitive functions and AQ, CFFT was used as the outcome variable and AQ, SAT performance and WAIS-IV processing speed index as the predictor variables in the first regression analysis. Given known deficits in executive function and flicker perception in Autism, AQ was used as the outcome variable in the second analysis, with CFFT, SAT performance and processing speed index being coded as the predictor variables.

Procedure

Participants were recruited via the University of Hull SONA system (Hull SONA Systems, 2020). On attending the laboratory, participants were provided with an information sheet (see appendix C) explaining what each task involves and a consent form which they needed to sign (see appendix D). Participants signed the consent form after being given the opportunity to ask any questions. Participants were informed of their right to withdraw in the information sheet up to the point of leaving the laboratory. All experimental test scores for each participant were indexed to a randomly-assigned six digit number; the participant's personal details from the consent form were not associated with this number. Hence, participants' data could not be withdrawn after the point that the participant left the testing session. Ethical approval for the study was given by the University of Hull's Faculty of Health Sciences ethics committee (FHS 220).

The order in which the participants moved through the various tasks was as follows: first, they completed the AQ questionnaire. The WAIS-IV (Wechsler, 2008) subtests were then given in counterbalanced order. The SAT was then completed, followed by the CFFT.

Upon completion of the study, participants were given a debrief form which explained the aims of the experiment and they were given the opportunity to ask any questions about this.

Critical flicker fusion threshold (CFFT)

To establish the participant's dominant eye participants were instructed to quickly place (visually) their index finger on a distant object whilst keeping both eyes open while the laboratory was lit at medium brightness by a desk lamp. By sequentially closing and opening each eye the dominant eye was determined by observing which eye's view caused the image of the finger to shift visually off the distant object (non-dominant) or remain visually on the distant object (dominant eye).

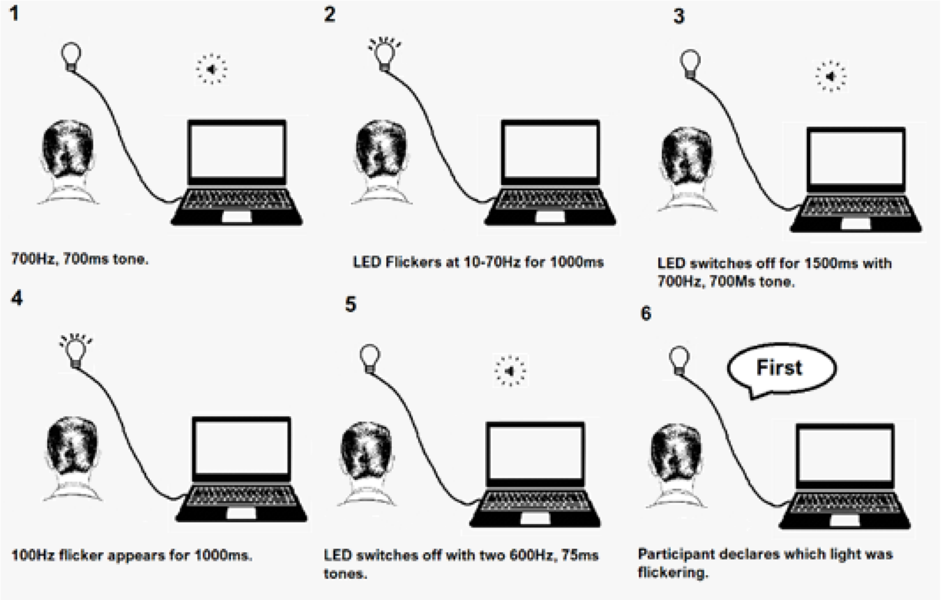
The laboratory lights and desk lamp were switched off when measuring participant's CFFT. The laboratory was provided with fully-lined curtains which were closed to keep out daylight. Participants were dark adapted for at least one minute in the fully darkened room before proceeding on to the CFFT task. The participant was asked to sit down in front of the mounted LED and to place their chin upon the fixed chin-rest. The chin-rest was adjusted to ensure that each participant's eye level was level with the LED. The LED was mounted at a viewing distance of 75 cm from the participant's dominant eye, meaning the LED subtended a visual angle of 0.38 degrees. The participants viewed the LED through a 3 mm-diameter aperture (artificial pupil) drilled through the centre of a 500 mm-wide square opaque segment of solid acrylic. A solid neutral density filter (1.2 ND) was firmly attached to the acrylic square so as to cover the central aperture reducing the effective illuminance of the LED incident to the participant's eye by a factor of 1/16 (equivalent to luminance of 2.68 cd/m^2). The acrylic square was held by the participant directly in front of and immediately before their dominant eye while they closed their non-dominant eye and also covered it with their free hand.

The CFFT was measured with a two-alternative forced-choice (2AFC) temporal task. Each trial consisted of two temporal intervals. For every trial in one of the two temporal intervals (pseudo-randomly chosen to be either the first or second interval) the LED would flicker sinusoidally at a fixed rate of 100 Hz (which is significantly above the human CFFT for a 5 mm-sized stimulus at a 2.68 cd/m^2 scotopic illuminance value (de Lange, 1958; Seitz *et al.,* 2006). The LED thus appeared to be steadily lit at a constant luminance to the participant. This is known as the steady *Reference* stimulus. In the other temporal interval, the same LED would flicker sinusoidally with a fixed temporal frequency which could change from one trial to the next. This is known as the *Test* stimulus.

In each trial, the participants were tasked with indicating which temporal interval (first or second) they thought the LED flickered (so they attempted to identify the Test stimulus). A 700 Hz tone with a duration of 700 ms preceded each flickering (Test stimulus) or steady (Reference) stimulus (separated by 1500 ms of auditory silence), and two 600 Hz beeps (both 75 ms separated by 100 ms of silence) sounded as a cue for the participants to state whether the LED bulb had flickered in the first or second interval. After ten reversals (incorrect trial followed by a correct trial, or *vice versa*) had taken place, a short combination tone played consisting of three 100 ms tones (1000 Hz, 1500 Hz, then 2000 Hz, each separated by 200 ms of silence). Figure 4 (page 25) shows a schematic of a trial.

Figure 4

Schematic of the CFFT task detailing how each trial progresses



Note: The flickering Test stimulus was in the first interval and the Reference stimulus (flickering at 100 Hz) was in the second interval. If the Test stimulus was below threshold the participant would have seen the Test stimulus flickering in the first interval and would therefore correctly identify the test stimulus by reporting 'first' interval.

Before the experiment proper began, each participant was presented with three practice trials where the LED in either the first or second interval flickered at a rate of 24 Hz (this was the Test stimulus and was slow enough for the flicker to be clearly perceptually apparent to the participant). The LED in the other trial interval flickered at a rate of 100 Hz (this was the Reference stimulus and the LED would have appeared perceptually to be steadily lit). This was done so that the participant understood the task. The experimental part of the test then started with the Test stimulus flickering at 24 Hz. After the first trial the frequency of the temporal flicker of the Test stimulus was determined by a 3up/1down staircase (Treutwein, 1995). Three consecutive correct detections of the Test stimulus interval by the participant resulted in an increase in the temporal flicker frequency of the Test stimulus. Failure by the participant to correctly detect the interval in which the Test stimulus appeared resulted in a decrease in the temporal flicker frequency of the Test stimulus. The initial four reversals (switch between increasing or decreasing direction) of the staircase used a step size of 4 Hz, followed by a step size of 2 Hz for the final six reversals. The mean of the last 6 of the 10 reversals was used to define the CFFT which was equal to 79% correct detection of the temporal interval containing the flickering LED (Test stimulus). The participant verbally responded at the end of each trial as to which interval (first or second) the LED had flickered and the researcher pressed the corresponding key for the first or second interval. The experiment was thus self-paced. There was no feedback. The CFFT of each participant was measured twice in succession. Where the CFFT is reported it is the mean of these two separately measured CFFTs in each participant’s dominant eye.

Shifting Attention Task (SAT)

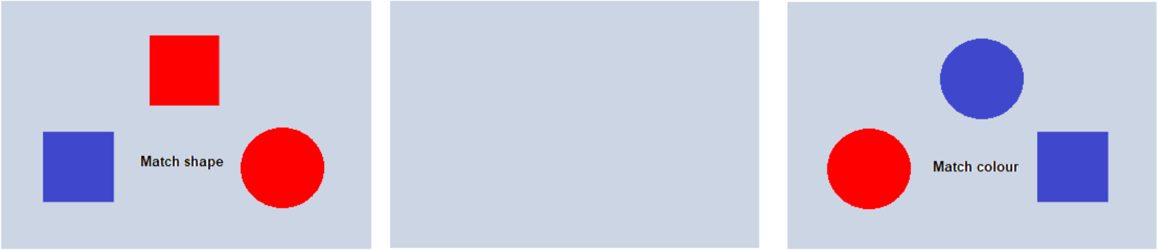
A custom version of the SAT (Gualtieri & Johnson, 2006) was programmed in Psychopy3 (Peirce *et al.,* 2019). Stimuli were presented on a 34.2 cm x 19.5 cm screen, with a pixel resolution of 1920 x 1080, at 5.61 pixels per millimetre vertically and 5.53 pixels per millimetre horizontally. At a viewing distance of 50 cm, each pixel subtended to approximately 0.02° of visual angle (vertically and horizontally) and the vertical refresh rate was 60 Hz.

The SAT required the participant to make a simple decision which was subject to trial by trial change. All trials presented the participant with a rule to make a decision (“match colour” or “match shape”) in black Arial font (1.69° of vertical visual angle) in the centre of the screen on each trial (see figure 5, page 27). There were three stimuli on the screen in each trial, which were either a red (RGB values: 254, 0, 0) or blue (RGB: 63, 71, 204) circle or square, with two selection stimuli, one in the middle-left of the screen, and the other on the middle-right. The background colour was pastel-grey (RGB values: 199, 191, 230). Both circles and squares, when presented as selection shapes subtended 4.06° of visual angle both horizontally and vertically. When presented as the rule shape in the top-centre of the screen, squares and circles subtended to 4.06° horizontally by 4.01° vertically). The rule shape subtended to 6.28°

in height and 6.19° in width). The rule shape (either red or blue circle or square) was presented in the top-centre of the screen (6° vertical offset) whereas the left shape stimulus and right selection shape were presented at 6.8° left and right offset from centre.

Figure 5

Schematic of the arrangement of two SAT trials with explanation of correct responses



The correct response is to press the 'A' key, because the blue square matches the rule and rule shape (top middle).

500ms Interstimulus interval (ISI) begins immediately after a resonse is made. Screen is cleared of all shapes.

Two selection shapes and a rule shape appear and have changed randomly at the end of the 500ms ISI. The correct response is the 'L' key, because the blue square (right) corresponds to the rule shape (top-middle).

Note: Figure represents two trial with an ISI as it appears on the screen.

There were 16 possible different types of trial ([square or circle] x [red or blue] x [match colour or match shape] x [left or right], = 2 x 2 x 2 x 2). Participants were instructed to indicate whether the left or right stimuli matched the top-centre stimulus using the centrally-presented rule. The ‘A’ key was pressed for when the left stimulus was correct whereas the ‘L’ key was pressed for when the right stimulus matched the rule. All responses were self-paced. There were 4 blocks of 48 trials, each trial separated by a 500 ms interstimulus interval (ISI) after each trial. The reaction times and correct responses of all trials were collected. A practice block consisting of 32 trials and no feedback preceded the four blocks. All conditions were counterbalanced ensuring that there were no more than three repeats of the same trial type in each block. No feedback was given after each trial, block or after completion of the task.

Measures

Autism-Spectrum Quotient (AQ)

The adult version of Baron-Cohen et al. (2001) Autism-Spectrum Quotient (AQ) was administered as a non-clinical measure of autistic traits (see appendix B). Participants were asked to complete all statements in the paper-based questionnaire by circling the answer which best applied to them. The four possible answers were “definitely agree”, “slightly agree”, “slightly disagree” and “definitely disagree”.

WAIS-IV Subtests

Visual processing speed was measured using three of the subtests from the fourth version of the Wechsler Adult Intelligence Scale (WAIS-IV; Wechsler, 2008). These subtests consisted of the core tests of symbol-digit coding and symbol search, and the supplementary subtest of cancellation. All three subtests tap into the visual processing component of intelligence (Wechsler, 2008).

Results

Statistical analyses

The main focuses of this investigation were to determine whether there was a relationship between AQ and CFFT, and to examine the link between executive function, processing speed and CFFT. Bivariate correlations were used, along with standard multiple regression analysis to investigate the interactions.

For calculation of the processing speed index, the z-scores for each of the three tests was calculated and the mean across these was used as the processing speed index. The mean reaction times for correct responses on the Shifting Attention Task was used as a measure of executive function. See table 1 (page 30 for details of how each variable was operationalised).

Findings

In this sample of young adults (mean age: 20.57 years, SD: 2.12, Range: [18 - 25]), the mean AQ was 18.93 (SD: 5.97, Range: [11 - 40]). This compares to a control sample in Baron-Cohen *et al.'s* (2001) study (mean age: 37.0 years SD: 7.7, Range: [18.1 - 60.0], Mean AQ: 16.4, SD: 6.3). The mean CFFT for left eye-dominant participants was 31.21 Hz (SD: 5.44), whereas the mean CFFT for right eye-dominant participants was 31.6 Hz (SD: 4.12). Independent t-tests were conducted to test for differences in CFFT by eye-dominance; these were insignificant ($t(26) = -.212$, 95% CI: [-.39, 1.85], $p = .83$). CFFT was measured twice in the participants' dominant eye and calculated from the mean over both calculations. The mean CFFT for the first measurement was 31.06 Hz (SD: 4.53), whereas for the second measurement, mean CFFT was 31.73 Hz (SD: 6.6). A paired sample t-test showed no significant difference between both measurements (t(26) = -.59, 95% CI = [-3.0, 1.67], p = .56). The mean CFFT overall was 31.39 Hz (SD = 4.8, Range = [22.83 - 41.67]). There were no speed-accuracy trade-offs for the SAT, as shown by a nonsignificant correlation between reaction times and accuracy (*r*(26) = .09, *p* = .67). See table 1 (below) for full descriptive statistics.

Table 1

Descriptive statistics

	Mean	SD	Min	Max
Age [years]	20.57	2.12	18	25
Critical Flicker Fusion Threshold (CFFT) [Hz]	31.39	4.79	22.83	41.67
Autism Spectrum Quotient (AQ) [test score]	18.93	5.97	11	40
SAT Reaction Times [milliseconds]	1169.56	295.54	730	1950
SAT Correct Responses [test score]	178.93	5.38	169	187
Symbol Digit Coding [test score]	79.64	13.21	42	106
Symbol Search [test score]	35.96	6.49	15	47
Cancellation [test score]	41.29	6.7	26	60

Note: Min-max scores: AQ [0-50], SAT correct responses [0-188], Symbol digit coding [0-135], Symbol Search [0-60], Cancellation [0-72]

Correlations

Firstly, bivariate Pearson correlations were conducted between all covariables including CFFT, AQ and SAT reaction times. See table 2 (below) for correlations between these variables. See table 3 (page 31) for correlations between scores on all three processing speed index tests.

Table 2

Correlations (r) between main covariables

Variable	1.	2.	3.
1. Critical Flicker Fusion	-	-	-
2. SAT Reaction Times	.03	-	
3. Autism Spectrum Quotient	.22	.10	-
4. Processing Speed Index	-.30	-.77**	-.25

Note. ***p* <.001

Table 3

Correlations (r) between WAIS-IV processing speed index subtests

Sub test	1.	2.
1. Cancellation	-	-
2. Symbol Digit Coding	.51**	-
3. Symbol Search	.59**	.41*

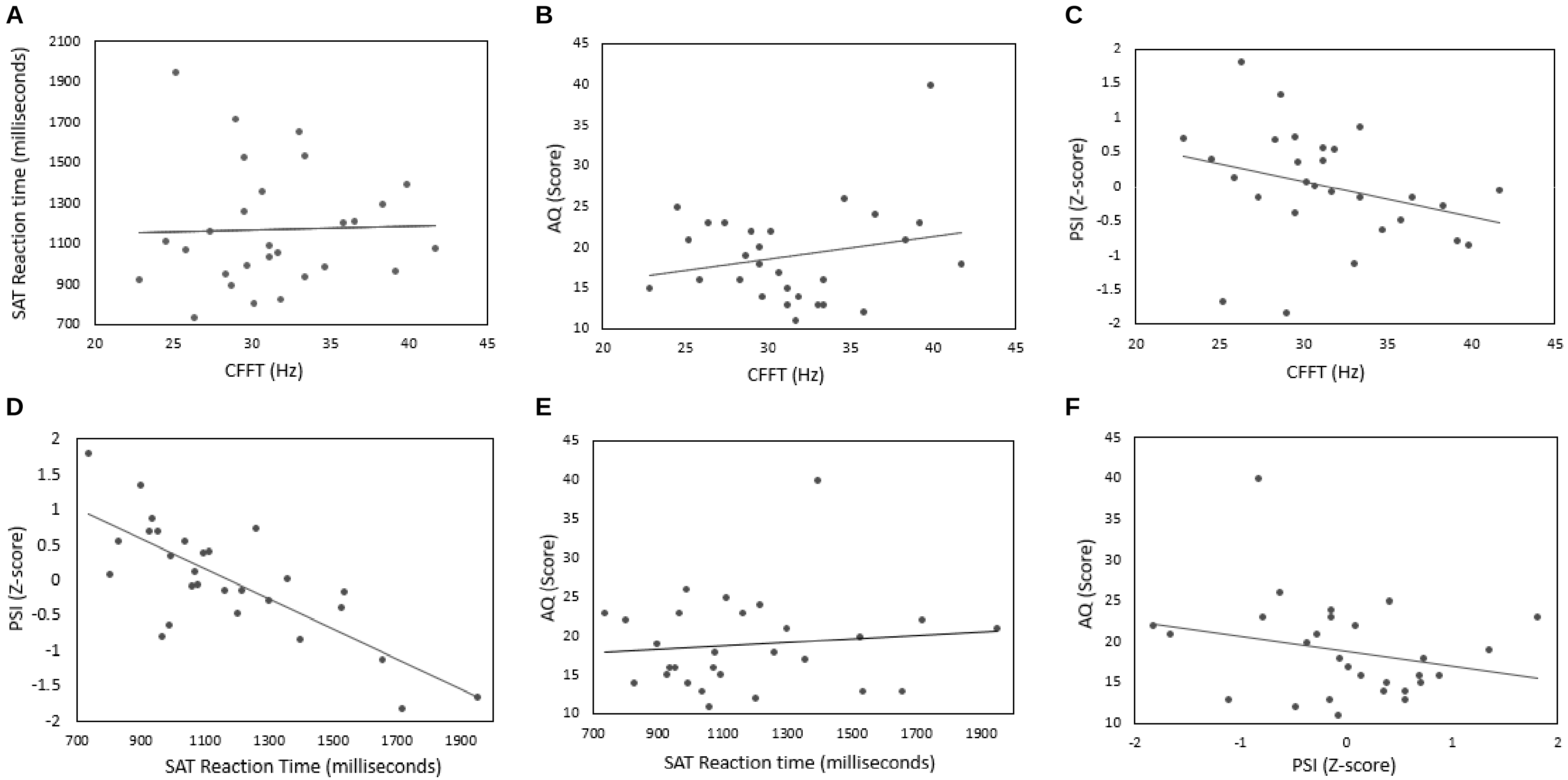
Note. **p* <.05, ***p* <.01

The only significant correlation between our main covariables was an inverse relationship between SAT performance and WAIS-IV processing speed index ($r(26) = -.770$, $p < .001$).

There was a weak positive correlation between AQ and CFFT, though this was not significant ($r(26) = .219$, $p = .131$). There was a slight positive nonsignificant correlation between CFFT and SAT reaction times ($r(26) = .033$, $p = .434$). There was a low positive nonsignificant correlation between AQ and SAT reaction times ($r(26) = .104$, $p = .299$). Correlations between CFFT and processing speed index were negative and nonsignificant ($r(26) = -.299$, $p = .061$), as were correlations between processing speed index and AQ ($r(26) = -.248$, $p = .101$). See figure 6, (page 32) for graphs of these correlations.

Figure 6

Correlational graphs with regression lines



Each dot shows an individual participant. **(A).** CFFT as a function of SAT reaction times (milliseconds). **(B).** CFFT as a function of AQ (score). **(C).** CFFT as a function of Processing Speed Index (z-score). **(D).** SAT reaction time (milliseconds) as a function of Processing Speed Index (z-score). **(E).** SAT Reaction times (milliseconds) as a function of AQ (score). **(F).** Processing Speed Index (Z-Score) as a function of AQ (score).

Multiple regression analysis

A standard multiple regression was conducted to predict CFFT from SAT reaction times for correct responses, AQ and WAIS-IV processing speed index (see table 4, below). There was independence of residuals, as assessed by a Durbin-Watson statistic of 2.385. There was homoscedasticity as assessed visually from a plot of studentized residuals versus unstudentized predicted values. There was no multicollinearity, as assessed by tolerance values all greater than 0.1. No studentized deleted residuals were greater than ±3 standard deviations, nor were there any leverage values greater than 0.2 or Cook's Distance values larger than 1. Normality was confirmed with the inspection of a Q-Q plot. The multiple regression model was not significantly better than the default model at predicting the relationship between the predictors and outcome variable (F(3,24) = 1.957, *p* = .147).

The coefficients showed that only processing speed index on WAIS-IV was a significant predictor of CFFT, (Beta = - 3.669, *p* = .046) though this was an inverse relationship. Mean reaction times for correct responses on the SAT did not significantly predict CFFT (Beta = -.007, *p* = .124), nor did AQ (Beta= .090, *p* = .564). The overall model fit was R^2 = .197.

Table 4

Multiple regression results for CFFT

CFFT	*B*	95% CI for B		*SE B*	*β*	R^2	$\triangle R^2$
		LL	*UL*				
Model						.197	.096
Constant	38.449**	24.783	52.115	6.621	52.115**		
SAT RT	-.007	-.017	.002	.005	-.462		
AQ	.090	-.227	.406	.153	.112		
WAIS PSI	-3.669*	-7.226	-.073	1.743	-.627*		

Note. Model = "Enter" method in SPSS Statistics; B = Unstandardized regression coefficient; CI = confidence interval' LL = Lower limit; UL = upper limit; SE B = standard error of the coefficient; β = standardized coefficient; R^2 = coefficient of determination; $\triangle R^2$ = adjusted R^2. *p < .05, *p <.001

An additional standard multiple regression was run to predict AQ from CFFT, SAT reaction times for correct responses and WAIS-IV processing speed index (see table 5, page 34). Initially, the data of all participants were included and the assumptions were checked. The assumption of normality was not met, as observed from a visual inspection of the histogram. This was due to only one participant being over 3SD's above the AQ score (AQ of 40). After the removal of this outlier, there were no more outliers ± 3SD's. Therefore, the results for the multiple regression for AQ are reported.

There was an independence of residuals, as assessed by a Durbin-Watson statistic of 0.253. the assumption of homoscedasticy was met as observed visually from a plot of studentized residuals against unstudentized predicted values. No multicollinearity was present since all tolerance values were larger than 0.1. There were no studentized deleted residuals above or below 3 standard deviations and there were no leverage values greater than 0.1 or Cook's distance values above 1. The assumption of normality was also met, as confirmed by a Q-Q plot which showed a linear relationship.

In the overall model, CFFT, SAT reaction times and processing speed index did not significantly predict AQ (F(3, 23)= .634, *p* = .601). The multiple regression analysis showed that CFFT was not a significant predictor of AQ (Beta = -.147, *p* = .493), neither was reaction times for the SAT (Beta = -.005, p = .287) or processing speed index (Beta = -2.514, *p* = .183). The overall model fit was $R^2 = .076$.

Table 5

Multiple regression results for AQ

AQ	*B*	95% CI for B		*SE B*	*β*	R^2	$\triangle R^2$
		LL	*UL*				
Model						.076	-.044
Constant	28.953**	8.114	49.792	10.074**			
CFFT	-.147	-.583	.289	.211	-.153		
SAT RT	-.005	-.015	.005	.005	-.360		
WAIS PSI	-2.514	-6.306	1.276	1.833	-.468		

Note. Model = "Enter" method in SPSS Statistics; B = Unstandardized regression coefficient; CI = confidence interval' LL = Lower limit; UL = upper limit; SE B = standard error of the coefficient; β = standardized coefficient; R^2 = coefficient of determination; $\triangle R^2$ = adjusted R^2. ** p <.001

Discussion

The rationale of the study was to investigate the relationship between the Critical Flicker Function Threshold (CFFT) and executive function, autistic traits and processing speed. Of particular interest was the relationship between CFFT and executive function (as measured by performance on the Shifting Attention Task, SAT), and the relationship between CFFT and self-reported autistic traits. It was predicted that there would be an inverse relationship between CFFT and SAT reaction times, meaning that enhanced performance on the SAT would predict better CFFT scores (as per Mewborn *et al.*, 2015), and that there would be a negative correlation between CFFT and AQ (as per Thompson *et al.,* 2015). In the present study reported here, the sample, which consisted entirely of young adults and participants with AQ mostly within the normal range, showed a nonsignificant relationship between both CFFT-SAT and CFFT-AQ. This study also investigated whether processing speed, as measured by the processing speed index of the WAIS-IV, had any relationship with CFFT; it did not.

It was predicted that there would be an inverse relationship between CFFT and SAT reaction times. Instead, there was no significant relationship between SAT performance and CFFT. This is contrary to the findings of Mewborn *et al.* (2015) who found that there was a relationship between SAT performance and CFFT. The nonsignificant relationship in the multiple regression between CFFT and executive function in the present study does not support the notion that CFFT is related to executive function in young adults. This, along with there being no relationship of CFFT and processing speed (as measured by the processing speed index), does not support Salthouse's (1996a, 1996b) processing speed theory, in which processing speed is related to a number of higher-order cognitive functions. Although Salthouse (1996a, 1996b) did not discuss CFFT, the processing speed theory suggests that a person with a fast, efficient brain is able to undertake an increased number of operations and at a faster speed. Therefore, it is somewhat of a surprise that CFFT did not predict reaction times on the SAT or performance on the processing speed index. At face value, the latter finding may suggest that CFFT is an unreliable measure of processing speed tasks in which the person has a limited time in which to execute as many operations as possible, and tests of executive function in which the person is required to simultaneously set shift, update and inhibit incorrect responses. The SAT is also reliant on reaction time so it is possible that a person with a high CFFT score, who processes visual information at a fast rate with faster reaction times, would be able to make faster and more accurate decisions on the SAT. However, there are multiple alternative explanations to consider (see limitations section, page 43).

Additionally, Mewborn *et al.* (2015) used many other predictor variables in their investigation, such as verbal memory, visual memory, processing speed and global cognition in their multiple regression analysis, all of which yielded a nonsignificant interaction. This may lead one to make the case that Mewborn *et al.'s* (2015) were measuring the relationship between many variables in the hope of finding a significant relationship (*p*-hacking); it is not explained why CFFT may be a predictor of executive function, but not a predictor of the other cognitive functions in the regression analysis.

The present study showed no significant relationship between CFFT and processing speed ($r = -.30$, $p = > .05$) whereas Mewborn *et al.* (2015) observed a high, significant positive correlation ($r = .34$, $p < .05$) between these variables. Although these correlations differ in direction, there is only a slight difference in the numbers. Had the *r* value in the present study been the same, and the sample size had been sufficiently high, this result would have reached levels of significance. Mewborn *et al.*'s (2015) finding suggests that CFFT (a proxy measure of visual processing speed) may be a reliable measure of processing capacity. Additionally, the CNS-VS (Gualtieri & Johnson, 2006), which Mewborn *et al.* (2015) used includes an alternative version of the symbol digit coding task also seen in the WAIS-IV (Wechsler, 2008) as the measure processing speed. This version of the symbol digit substitution test is computerised, involving serial presentations of each rows for the participant to complete each item by pressing the corresponding number. Therefore, the difference in relationship between CFFT and processing, across both studies is unlikely to be due to this difference in method.

Since the studies by Mewborn *et al.* (2015) and Saint *et al.* (2019) have shown that processing speed is correlated with CFFT, it seems anomalous that there was a negative correlation between these variables, and an inverse relationship as observed in the multiple regression analysis for CFFT, since a high CFFT score would mean that the individual has a higher capacity to process more information over time (through the limited time mechanism; Salthouse, 1996a), and a brain which has faster neural firing rate, which operates more efficiently than somebody with a low CFFT. It would be logical that a positive correlation is present between any test on processing speed and CFFT yet this was not found in the present study. Although the negative correlation was nonsignificant, it was generally anticipated that any relationship between processing speed by proxy (which tests temporal visual processing as CFFT does) and processing speed (as measured by a cognitive test battery or index) would have, at least, a small-to-moderate positive correlation (Mewborn *et al,.* 2015; Saint *et al*., 2019). Such a finding would complement Salthouse's (1996a, 1996b) processing speed theory well, since it would show that a reduced capacity to process visual information over time (limited-time mechanism), and diminished ability to maintain the products of early processing (simultaneity mechanism) would lead to deteriorated performance on cognitive tests.

Saint *et al.* (2019) observed that cognitive efficiency (visual matching and numbers reversed performance), executive function (planning and cancellation performance) and processing speed (decision speed), all subtests from Woodcock-Johnson III tests of cognitive ability (Mather & Gregg, 2001) were all related to flicker threshold in young children (7 to 13 years of age). This was concluded as being evidence for the notion that there is a relationship between temporal vision and cognition. The results of the present study differ from Saint *et al.* (2019) in that there was no relationship between CFFT and executive function observed. Mewborn *et al.*'s (2015) correlation between CFFT and executive function (SAT) was more pronounced than Saint *et al.'s* (2019), (Mewborn *et al.,* 2015: r = .465; Saint *et al.,* 2019: r = .246) which Saint *et al.,* (2019) attributes to executive function being less developed in pre-adolescents than adults. Saint also suggested that executive function may not be suitable as a predictor of temporal visual processing speed in pre-adolescent children. Considering the comparison of the magnitude of the relationship between both studies, one may have expected a larger main effect in the present study reported here than was found in Saint *et al.'s* (2019) because the present study recruited adult participants, whose executive function skills would be likely to be more fully developed (Best & Miller, 2010).

In this study the CFFT mean score was 31.39 Hz which was considerably higher than Mewborn *et al.'s* (2015) mean CFFT of 25.96 Hz. While Mewborn *et al.* (2015) report that their mean fusion threshold scores was higher in comparison to a previous study (Renzi & Hammond, 2010), this was attributed to the high level of educational attainment in the sample, with most of the younger adult participants being university students, and the older adults generally reporting years of education (mean = 16.5 years) indicative of a university education. Although all of the participants in the present study were composed of a mixture of undergraduate and postgraduate students, the same attribution has not been made. The link between educational attainment and CFFT is unclear, with previous work showing no, or little, relationship. For example, Cautela and Barlow (1965) attempted to find a link between educational attainment in terms of admission test scores and CFFT but found no relationship, whereas Kumar *et al.* (2020) found there to be a small, positive correlation, between aptitude tests and CFFT (r = .19) in a large sample of medical and dental students. However, the aptitude tests used were about anatomy and physiology, so it may be argued that this was an unsuitable measure of educational attainment, since it only measured subject knowledge. Likewise, further investigation may be required to investigate this relationship further.

The nonsignificant correlation between CFFT and AQ in the present study raises some questions regarding the relationship between temporal processing speed and self-rated autistic traits, specifically among people within the neurotypical population. This observation is contrary to the finding by Thompson *et al.* (2015) who observed in a non-clinical sample of individuals in which a between-groups design showed that those in the group of highest self-rated AQ scores had diminished achromatic flicker perception in comparison to people with low AQ. The most pronounced difference in performance was for the achromatic flicker task with a low 5% contrast and amounted to a difference between ~35 Hz (for the low-AQ group) compared to ~31 Hz (for the high-AQ group). The nonsignificant correlation in the present study is similar to the findings by Pellicano *et al.* (2005) and Bertone *et al.* (2005), who also found no relationship between flicker thresholds and autism, albeit when groups design were used due to the comparisons being between autistic and neurotypical children. Thompson *et al.'s* (2015) study investigated the relationship between flicker and autistic traits by using AQ as a measure of autistic traits, recruiting from a non-clinical sample. The significant relationship in Thompson *et al's.* (2015) study may have led one to expect a significant finding in the present study. That none was found therefore calls into question whether AQ score is reliably predictive of CFFT. However, there are a few possibilities that may account for the discrepant results.

Thompson *et al's.* (2015) study had a narrow spread of AQ scores. Thompson *et al.* (2015) assigned participants to two different groups based on their AQ scores (low AQ $\leq$ 13; high AQ $\geq$ 18), and the mean AQ was 23.8 (SD = 4.47) for the low AQ group; 8.1 (SD = 3.79) for high group, the mean AQ in the current study was 18.93 (SD = 5.97). Additionally, the differences in flicker perception were quite low in the achromatic flicker task. For example in the 5% contrast condition, the difference in thresholds between the groups was approximately 4 Hz, and this was the most pronounced difference of any of the contrast levels. Finally, the possibility of Thompson *et al.'s.* (2015) finding being a false positive should be considered, as the present study suggests that there is no relationship between AQ and flicker perception, and the results from the paediatric studies also suggest this.

The method of measuring flicker perception in the literature differs with the paediatric studies, using 10 Hz stimuli (sinusoidal luminance grating in Bertone *et al.* 2005; Gaussian blob in Pellicano *et al.,* (2005) presented on a computer screen, and a CFFT experiment using a staircase paradigm with bespoke hardware solution using an LED in Thompson *et al.* (2015). The difference in stimulus type and stimulus delivery mean that there are concerns with how adequately Bertone *et al*. (2005) and Pellicano *et al*. (2005) could have measured flicker thresholds on methodological grounds – their presentation setup could easily have introduced artifacts (such as temporally-aliased frequencies due to insufficient temporal resolution which would confound their studies) and their restricted measure of flicker contrast sensitivity is a less comprehensive measure of flicker perception compared to a staircase-derived flicker perception fusion. For these reasons, Thompson *et al.* (2015) is the better study in terms of stimulus and hardware delivery. Thus although the present study replicated the procedural and experimental setup advantages of Thompson *et al.* (2015) and yet showed no relationship between AQ and CFFT one might want to conclude that there is no relationship. Taken together, the present study, along with Bertone *et al.* (2005) and Pellicano *et al.* (2005) suggest no relationship between autism and flicker perception (although the lack of power in the present study reduces the force of this claim). This is discussed later.

The results of Thompson *et al.'s* (2015) study also raise some further points. Based on their published results, it is not possible to ascertain whether a significant finding would still have been found, had they computed a correlation. While there was a small difference in mean thresholds between both groups, it is not known whether the relationship between AQ and flicker perception was correlational. Moreover, it is noteworthy that the mean AQ (18.93) in the present study is within +0.25 SD of the estimated mean score of the neurotypical population in Baron-Cohen *et al.'s* (2001) study (Mean AQ = 16.4, SD = 6.3), so it could be said that both studies have used a sample with people within the normal range of autistic traits. This can be said of the high AQ (AQ $\geq$ 18) group in Thompson *et al.'s* (2015) study, because the mean AQ in this group was 23.8 (SD = 4.47) indicating that these participants were not in the high range of AQ, although the low AQ group appeared to be within the low range (mean AQ = 8.1, SD = 3.79). A small difference in flicker thresholds for the achromatic flicker tasks at the lowest contrasts was found. This raises another question of whether a directional relationship would still be found in Thompson *et al.'s* (2015) study, had the cut-off points been higher for the high-AQ group. For example, in Baron-Cohen *et al.*'s (2001) study, the mean

AQ was much higher (mean AQ = 35.8, SD = 6.5), in the group composed of people with High-Functioning Autism or Asperger's syndrome), but based on these results, it cannot be known whether people within this range would have diminished achromatic flicker thresholds. Based on Thompson *et al.'s* (2015) findings, it cannot be ascertained whether a group of people with AQ in the high range would have diminished or enhanced (depending on type of flicker task) in comparison to a low AQ group. It may be beneficial for further research to investigate this relationship using groups with higher cut-off points for the high AQ group.

The only significant correlation in the present study was the inverse relationship between SAT reaction times and the WAIS-IV processing speed index (composite of z-scores across three tests). Although this was not a main focus of our investigation, this association may relate to Salthouse's (1996a) processing speed theory, in which it is argued that the brain is like a clock, and that a brain with a fast processing speed has the resources to complete cognitive tasks quickly and with ease. In this case, the better the participants performed on the processing speed index, the faster their reaction times were for correct responses on the SAT. Since there were no speed-accuracy trade-offs, these faster reaction times were not related to accuracy. This finding also relates to the early and recent studies which link reaction time to intelligence, since the processing speed index is a subtest from the WAIS-IV intelligence test (Deary *et al.,* 2001; Der & Deary, 2017; Jensen & Munro, 1979; Neubauer, 1990). This finding also suggests that processing speed is related to executive function (specifically, set-shifting).

This study is one of a small number of investigations that used a custom-made device for measuring CFFT. A strength to this study is that it shows how this can be accomplished in a cost-effective manner, in a similar manner accomplished by Teikari *et al.* (2012), who also developed their own custom-made software using Arduino-based hardware for this purpose. Eisen-Enosh *et al.* (2017) also generated their flicker stimuli in a similar manner albeit using MATLAB rather than Python.

Limitations

The sample size of the current study is small compared to similar studies (159 in Mewborn *et al.,* 2015; 36 in Pellicano *et al.,* 2005; 51 in Saint *et al.,* 2019; 39 in Thompson *et al.,* 2015), which could have affected the heterogeneity of our participants. This was due to the Coronavirus pandemic; testing was stopped prematurely due to lockdown rules and the researcher was unable to access the laboratory. Consequently, this study is underpowered. This may explain the nonsignificant findings in the correlations and multiple regressions. For a multiple regression with three predictor variables, the sample size should be at least 119 to have sufficient power to yield a genuine 95% confidence interval, when calculated by the software G*Power (Version 3.1.9.4; Faul *et al.,* 2007; Faul *et al.,* 2009; Heinrich Heine University Düsseldorf, 2020). Nonetheless, it was appropriate to check the normality and other assumptions for the regression analyses, which were met for the first, and second regression model (albeit after removing an extreme outlier from the dataset).

The majority of participants in the present study had AQ scores within ±2 standard deviations of the mean (27 participants within the normal range, and 1 with an AQ of 40 which is +3 SD's from the mean) so were within the neurotypical range, and are comparable to the control sample group who were rated as having low autistic traits in Baron-Cohen *et al.'s* (2001) study (Present study: Mean AQ = 18.93, STD = 5.97; Baron-Cohen: Mean AQ = 16.4, STD = 6.3). This may have affected the generalizability of the study and could explain why there was no significant relationship between AQ and CFFT. The same may be argued of Thompson *et al.'s* (2015) sample where the AQ scores also appeared to fit within the neurotypical range when dichotomising the sample into two groups ('low AQ' ≤ 13 and 'high AQ' ≥ 18). Most volunteers were psychology undergraduate students which could partially explain the low spread of AQ scores - previous work by Baron-Cohen *et al.* (2001) has shown that students with high self-rated autistic traits are more likely to choose STEM subjects such as physics, computer science and mathematics whereas participants with low AQ were more likely to be studying humanities-based subjects.

Future directions

There have been relatively few previous studies which have attempted to measure the relationship between CFFT and executive function (Mewborn *et al.,* 2015; Saint *et al.,* 2019). To gain a deeper understanding of the relationship between CFFT and executive function, there should be additional studies which use different tests to measure this higher-order cognitive function, to establish whether the type of measure has any effect on the findings. It would also be beneficial to investigate which specific domains of executive function are related to visual processing speed, such as inhibitory control, working memory, and cognitive flexibility. Using tests of executive function which use only one of these domains could help researchers to investigate which of these relate to visual processing speed.

While Mewborn *et al.* (2015) investigated the relationship between flicker perception and higher-order cognitive functions with the use of tasks from the CNS-VS (Gualtieri & Johnson, 2006), there is some potential to apply different test batteries which measure a range of cognitive functions such as executive function, memory, psychomotor speed and reasoning. For example, researchers could include the Cambridge Neuropsychological Test Automated Battery (CANTAB; Cambridge Cognition, 2020) as their chosen method of measuring cognitive function. This battery includes a task which measures rapid visual information processing (RVP) which may be of particular interest, since CFFT is considered to be a test of proxy visual processing speed. Such research could be used to contribute to existing research about the relationship between visual processing and higher-order cognitive functions (Albinet *et al.,* 2015; Salthouse, 1996a, 1996b).

The present experiment used the SAT as a measure of executive function. The SAT measures three core aspects of executive function (set-shifting, updating and inhibition). For this reason, it may be argued that in the present study and in Mewborn *et al.'s* (2015) study the relationship between CFFT and *some* core executive functions has only been investigated. Therefore, there is scope for additional research seeking to determine whether other core executive functions such as interference control, planning and cognitive flexibility relate to flicker perception. Recruiting tasks which isolate any of these executive functions would help researchers to develop a clearer picture of this relationship. Salthouse's (1996a) processing speed theory proposes that processing speed is related to a number of cognitive functions; any further research which measures the relationship between CFFT and multiple executive functions could further test the assumptions of this theory.

The present study and Mewborn *et al.'s* (2015) study examined the relationship between achromatic flicker perception (magnocellular functioning) and CFFT. As shown by Thomson *et al.* (2015), CFFT can also be measured with the use of a colour-fusion task (parvocellular functioning), whereas Pellicano *et al.* (2005) measured this with the use of a Gaussian blob. Studies which use different methods measuring magnocellular and parvocellular functioning by administering various types of flicker tasks could be beneficial in discovering more about the role of autistic tendencies in parvocellular and magnocellular processing, further detangling the relationship between different aspects of flicker perception and how this might influence executive function.

Researchers may wish to consider what measures of autism or autistic symptomatology are used in future work. There is the option to measure this correlationally or in a regression model, as in the current study, or to dichotomise participants into two groups (high- or low-AQ as in Thompson *et al.,* 2015, or an ASD and control group in Bertone *et al.,* 2005 & Pellicano *et al.,* 2005). At present, there have been no published studies which have attempted to measure the role of autistic traits and flicker perception correlationally. Such studies should, however, control for the possible effects of executive function and processing speed (Mewborn *et al.,* 2015; Saint *et al.,* 2019).

Thompson *et al.* (2015) found a significant relationship between flicker perception in a between-groups design experiment, segregating participants into groups depending on their AQ. The small difference between the cut-off points in AQ scores for both groups may leave some doubt on whether differences in flicker perception could be due to autistic traits. Additional research should investigate this relationship further, to ascertain whether any additional factors such as executive function (Mewborn *et al.,* 2015; Saint *et al.,* 2019), processing speed or other implicated factors influence flicker perception. Therefore, it is suggested that any investigation of CFFT and higher-order cognitive functions should also investigate for the potential effect of autism symptomatology (whether using self-rated measures or clinical groups), and *vice versa*.

More investigation is required to ascertain whether autistic diagnosis relates to flicker perception. Gaining access to clinical population groups could be difficult, however this should resolve the possible caveat of relying on self-rated autistic traits. Moreover, participants with severe autism could not be used in further research due to the possible confound of being unable to understand the task. As such, participants who have a diagnosis of the condition who are likely to sit within the normal IQ range should be recruited. These participants could be university students (who may be willing to take part to earn course credits) or members of the public. One possible caveat to investigating the role of a diagnosis of ASD though could be that sometimes the disorder may go undiagnosed, or possibly misdiagnosed; lack of a diagnosis does not mean that no disorder or symptoms (such as RRB’s) are present. This is one advantage of using a self-reported measure of autistic traits such as AQ has over using clinical samples, since the extent of the autistic traits can be measured.

Some previous work which has investigated the relationship between flicker perception and autism and various cognitive processes have recruited child participants (Pellicano *et al.,* 2005; Saint *et al.,* 2019) whereas others have recruited adults (Bertone *et al.,* 2005; Halstead, 1947; Mewborn *et al.,* 2015; Tanner, 1950; Zlody, 1965). It may be beneficial to investigate the role of age in this relationship, possibly recruiting older and younger participants in the process. This is because Albinet (2012) observed that the relationship between processing speed (as measured by choice reaction time) and set shifting, and other measures of cognitive function, can be mediated by age. Furthermore, Saint *et al.* (2019) proposed that the relationship between CFFT and executive function, and other measures of cognition, is less pronounced in pre-adolescent participants than it is in adults (Mewborn *et al.,* 2015). Despite this, the relationship between CFFT and executive function did not differ in old or young adults in Mewborn *et al.'s* (2015) investigation. Further investigation could help to fully understand whether flicker perception predicts higher-order cognitive functions.

To date, there have been few studies which have demonstrated an alternative to measuring CFFT with an expensive commercial device which have explained the process in some detail (Demontis & Cervetto, 2005; Eisen-Enosh *et al.,* 2017; Teikari *et al.,* 2012) though with not sufficient detail to produce a replication of flicker stimuli in the same way as has been produced in their experiment. Therefore, the experimenter is faced with the task of learning how to produce flicker stimuli and custom-made experiments, presumably with the use of tutorials in the software and use free resources such as Youtube. Any academic resource which gives enough detail within the method section or appendix to make a suitable flicker experiment would be beneficial to researchers who do not have access to a commercial device.

Conclusion

This study investigated whether there was a relationship between CFFT and autistic traits, executive function (as measured by the SAT), and visual processing speed (as measured by the WAIS-IV processing subtests). Previously, there has been some research measuring the relationship between flicker perception and autism (Bertone *et al.,* 2005; Pellicano, *et al.,* 2005), CFFT (achromatic and dichromatic) and autistic traits (Thompson *et al.,* 2015), and others which have investigated the relationship between CFFT, processing speed and executive function (Mewborn *et al.,* 2015; Saint *et al.,* 2019). Conducting a multiple regression made it possible to investigate the extent to which predictor variables (AQ, SAT and processing speed) predict CFFT and how CFFT, SAT and processing speed index (as predictor variables) measure AQ.

Although the results did not fit the predictions, it is too early to make any definite conclusions about the relationship between CFFT and executive function and processing speed, and CFFT and AQ. Future work should incorporate a variety of different methods of measuring CFFT and a range of core executive functions. In the future, researchers should attempt to recruit large groups of participants (ensuring sufficient statistical power) while attempting to gain access to a heterogeneous population which should include participants with low and high AQ. Ideally, such future research should shed further light on the relationship between CFFT, autism and executive function.

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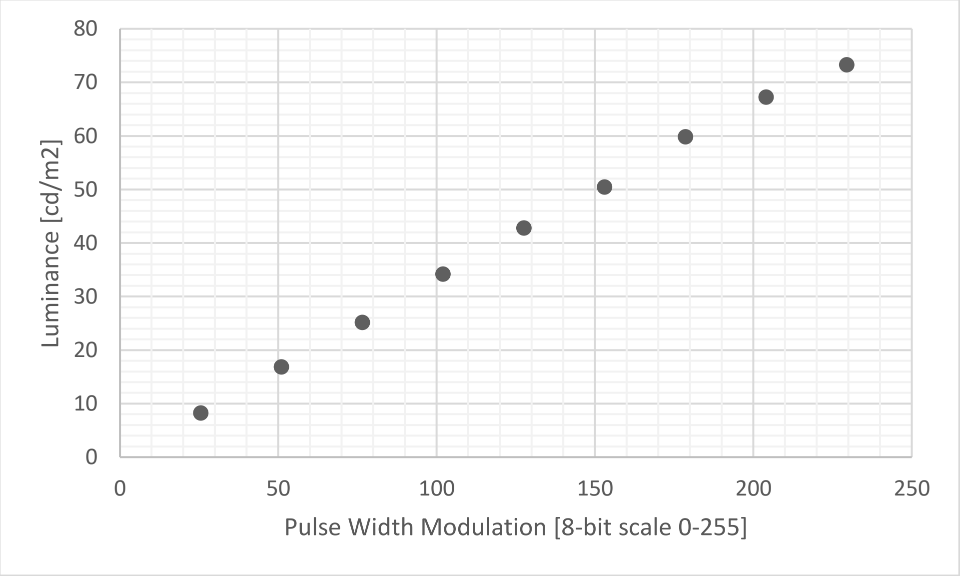
Appendix A – Technical Details of Arduino Microcontroller

The Arduino Uno™ microcontroller was used to measure the luminance (cd/m^2) of the LED at ten different brightness levels in a fully darkened space (see graph 6, below). The signal properties of the waveform produced on the digital pin 3 of the Arduino Uno™ were verified with the use of a 40 Mhz Digimess MO40 oscilloscope (serial number: 03101041).

Graph 6

PWM (Pulse Width Modulation [8-bit scale 0-255]), as a function of luminance cd/m^2.



Note. The scatter is linear at the r=.999 level

Appendix B – AQ Scale

Version 1. Date: 16/12/2019

Age [in years]: ______

How would you describe your gender (M / F/ Non-Binary / Prefer self-describe / Prefer not to say]: _______________

Student or Staff [student/staff]: ______

If Student what Subject [please list Dept.]: ______

Random Participant Number: ______

Below is a list of statements. Please read each statement carefully and rate how strongly you agree or disagree with it by circling your answer. If you incorrectly circle an answer you don’t feel you agree with any longer, place a cross through the answer, and circle the correct answer.

Do not miss any statement out.

Examples

E1. I am willing to take risks.	definitely agree	slightly agree	[✓ slightly disagree]	definitely disagree
E2. I like playing board games.	definitely agree	[✓ slightly agree]	slightly disagree	definitely disagree

E3. I find learning to play musical instruments easy.	definitely agree	slightly agree	slightly disagree	[✓ definitely disagree]
E4. I am fascinated by other cultures.	[✓ definitely agree]	slightly agree	slightly disagree	definitely disagree

The next page is the real questionnaire – please carry on when you are ready. Answer as quickly as possible after reading each statement – go with your gut instinct as to how it applies to you. You Don’t need to think deeply about it. There are 50 statements.

1. I prefer to do things with others rather than on my own.	definitely agree	slightly agree	slightly disagree	definitely disagree
2. I prefer to do things the same way over and over again.	definitely agree	slightly agree	slightly disagree	definitely disagree
3. If I try to imagine something, I find it very easy to create a picture in my mind.	definitely agree	slightly agree	slightly disagree	definitely disagree
4. I frequently get so strongly absorbed in one thing that I lose sight of other things.	definitely agree	slightly agree	slightly disagree	definitely disagree
5. I often notice small sounds when others do not.	definitely agree	slightly agree	slightly disagree	definitely disagree
6. I usually notice car number plates or similar strings of information.	definitely agree	slightly agree	slightly disagree	definitely disagree
7. Other people frequently tell me that what I’ve said is impolite, even though I think it is polite.	definitely agree	slightly agree	slightly disagree	definitely disagree
8. When I’m reading a story, I can easily imagine what the characters might look like.	definitely agree	slightly agree	slightly disagree	definitely disagree

9. I am fascinated by dates.	definitely agree slightly agree slightly disagree definitely disagree
10. In a social group, I can easily keep track of several different people's conversations.	definitely agree slightly agree slightly disagree definitely disagree
11. I find social situations easy.	definitely agree slightly agree slightly disagree definitely disagree
12. I tend to notice details that others do not.	definitely agree slightly agree slightly disagree definitely disagree
13. I would rather go to a library than to a party.	definitely agree slightly agree slightly disagree definitely disagree
14. I find making up stories easy.	definitely agree slightly agree slightly disagree definitely disagree

15. I find myself more drawn to people than to things.	definitely agree slightly agree slightly disagree definitely disagree
16. I tend to have very strong interests, which I get upset about if I can't pursue.	definitely agree slightly agree slightly disagree definitely disagree
17. I enjoy social chitchat.	definitely agree slightly agree slightly disagree definitely disagree
18. When I talk, it isn't easy for other's to get a word in edgewise.	definitely agree slightly agree slightly disagree definitely disagree

19. I am fascinated by numbers.	definitely agree	slightly agree	slightly disagree	definitely disagree
20. When I'm reading a story, I find it difficult to work out the characters' intentions.	definitely agree	slightly agree	slightly disagree	definitely disagree
21. I don't particularly enjoy reading fiction.	definitely agree	slightly agree	slightly disagree	definitely disagree
22. I find it hard to make new friends.	definitely agree	slightly agree	slightly disagree	definitely disagree
23. I notice patterns in things all the time.	definitely agree	slightly agree	slightly disagree	definitely disagree
24. I would rather go to the theatre than a museum.	definitely agree	slightly agree	slightly disagree	definitely disagree
25. It does not upset me if my daily routine is disturbed.	definitely agree	slightly agree	slightly disagree	definitely disagree
26. I frequently find that I don't know how to keep a conversation going.	definitely agree	slightly agree	slightly disagree	definitely disagree
27. I find it easy to "read between the lines" when someone is talking to me.	definitely agree	slightly agree	slightly disagree	definitely disagree
28. I usually concentrate more on the whole picture, rather than the small details.	definitely agree	slightly agree	slightly disagree	definitely disagree

29. I am not very good at remembering phone numbers.	definitely agree	slightly agree	slightly disagree	definitely disagree

30. I don’t usually notice small changes in a situation or a person’s appearance.	definitely agree	slightly agree	slightly disagree	definitely disagree
31. I know how to tell if someone listening to me is getting bored.	definitely agree	slightly agree	slightly disagree	definitely disagree
32. I find it easy to do more than one thing at once.	definitely agree	slightly agree	slightly disagree	definitely disagree
33. When I talk on the phone, I’m not sure when it’s my turn to speak.	definitely agree	slightly agree	slightly disagree	definitely disagree
34. I enjoy doing things spontaneously.	definitely agree	slightly agree	slightly disagree	definitely disagree
35. I am often the last to understand the point of a joke.	definitely agree	slightly agree	slightly disagree	definitely disagree
36. I find it easy to work out what someone is thinking or feeling just by looking at their face.	definitely agree	slightly agree	slightly disagree	definitely disagree
37. If there is an interruption, I can switch back to what I was doing very quickly.	definitely agree	slightly agree	slightly disagree	definitely disagree
38. I am good at social chitchat.	definitely agree	slightly agree	slightly disagree	definitely disagree
39. People often tell me that I keep going on and on about the same thing.	definitely agree	slightly agree	slightly disagree	definitely disagree
40. When I was young, I used to enjoy playing games involving pretending with other children.	definitely agree	slightly agree	slightly disagree	definitely disagree
41. I like to collect information about categories of things (e.g., types of cars, birds, trains, plants).	definitely agree	slightly agree	slightly disagree	definitely disagree

42. I find it difficult to imagine what it would be like to be someone else.	definitely agree	slightly agree	slightly disagree	definitely disagree

43. I like to carefully plan any activities I participate in.	definitely agree	slightly agree	slightly disagree	definitely disagree
44. I enjoy social occasions.	definitely agree	slightly agree	slightly disagree	definitely disagree
45. I find it difficult to work out people’s intentions.	definitely agree	slightly agree	slightly disagree	definitely disagree
46. New situations make me anxious.	definitely agree	slightly agree	slightly disagree	definitely disagree
47. I enjoy meeting new people.	definitely agree	slightly agree	slightly disagree	definitely disagree
48. I am a good diplomat.	definitely agree	slightly agree	slightly disagree	definitely disagree
49. I am not very good at remembering people’s date of birth.	definitely agree	slightly agree	slightly disagree	definitely disagree
50. I find it very easy to play games with children that involve pretending.	definitely agree	slightly agree	slightly disagree	definitely disagree

Appendix C – Information sheet for study

Version 1.1 Date: 17/12/2019

UNIVERSITY OF HULL

Department of Psychology

PARTICIPANT INFORMATION SHEET

YOU WILL BE GIVEN A COPY OF THIS INFORMATION SHEET

Title of Study: **Perceptual and cognitive functioning as a function of personality**

Researcher: **Mr Sam Cowling**

Supervisor: **Dr David Smith**

You have been invited to take part in a research project which forms part of my research. Before you decide whether you want to take part it is important for you to understand why the research is being done and what your participation will involve. Please take time to read the following information carefully and discuss it with others if you wish. Ask me if there is anything that is not clear or if you would like further information.

What is the purpose of the study?

The purpose of the study is to understand how certain perceptual and cognitive measures are related to various personality styles.

Why have I been invited to take part?

You are being invited to participate because you are an English-speaking adult (over the age of 18) who can provide representative data for the research question being investigated. Because of the nature of this study you can only take part if you have normal, or corrected-to-normal vision, with no known history of colour blindness. You will need to wear your corrective lenses (glasses or contact lenses) during the experimental session.

What will happen if I take part?

You will be asked to do a series of perceptual and cognitive tasks, as well as fill out a questionnaire. These tasks and questionnaire are as follows:

The perceptual measure we are interested in is how fast a small light has to flicker (turn on and off repeatedly) before you cannot see it flickering on and off. You will be asked to view a small LED bulb whilst looking through a small viewing hole. To maintain the right viewing distance you will need to place your chin on a rest. You will need to wear headphones during the perceptual test. First the researcher will make the LED flicker so that you know what it looks like when the LED flickers. The perceptual experiment proper will start with you hearing a short beep during which the LED *may* flicker quickly followed by another short beep after which the LED *may* flicker. The two sounds mark two short briefs periods of time when the LED was flickering visibly EITHER in the first or second interval. Whether the LED flickers in the first or second interval is completely random, and it is *never* the case that the LED flickers visibly in both intervals. You simply have to declare which interval (first or second) the LED flickered. The experimenter will repeatedly ask you whether the LED flickered in the first or second interval. At first it will be easy but over time it will become increasingly harder to say in which interval the LED flickered because the flicker rate will be increased depending on your performance. That the task becomes harder is to be expected – however, rest assured there will always be one interval in which the LED flickered even if you cannot tell in which interval it was flickering. In cases where you are unsure of which interval it flickered please go with your gut instinct rather than just guessing the same thing repeatedly. You will be surprised how good you will be at the task. When the controlling programme determines that you have reached the flicker rate at which you are unable to tell whether the LED is flickering or not then the programme will automatically stop. This perceptual test should take about 10 min to complete.

The cognitive tasks will involve a nonverbal reasoning task in which you will be asked to identify patterns in designs, another task where you will be asked to rapidly search for symbols, and another task in which you will asked to match stimuli at the top of a computer screen with other stimuli at the bottom of the screen based on a set of matching rules (i.e., match colour or match shape) that change randomly. For all tasks you will be given practice examples so that you should understand what you are meant to do.

You will be also be asked to complete a questionnaire that covers aspects of your personality and how you organise your social life, communicate with your peers and family and the types of hobbies you may have.

Participation will take place in a research laboratory in the Applied Sciences 3 building at the University of Hull. This study will take place in one session lasting between 45-60 min where all five tasks will be completed. As part of participation you will be asked to provide your name and signature for consent to take part. Your name will not be linked to any performance measures – that is done entirely anonymously.

Do I have to take part?

Participation is completely voluntary. You should only take part if you want to and choosing not to take part will not disadvantage you in any way. Once you have read the information sheet, please contact us if you have any questions that will help you make a decision about taking part. If you decide to take part you will be asked to sign a consent form saying you understand what participation will involve.

Payment/Incentives

For taking part you will receive 1 hour of research hours credit via the SONA system.

What are the possible risks of taking part?

There are no known risks associated with participating in this experiment.

What are the possible benefits of taking part?

There are benefits to you individually as a result of participating in this study through a better understanding of the research process in psychology. Your research data will help the scientific community's understanding of various aspects of perceptual and cognitive functioning, and how they may be associated with different personality styles.

Data handling and confidentiality

Your data will be processed in accordance with the General Data Protection Regulation 2016 (GDPR). All your data will be kept and remain confidential. Any identifiable personal data will stored securely and will only be available to the immediate research team. Any personal data will be destroyed within five years. Anonymised research data may be kept indefinitely. The research data will not be linked to you as the data will be stored anonymously. There is nothing to identify the data as coming from you, as your name or any personally identifiable information is not stored together. Your research data (anonymous data not linked to you) may be used to support future research and may be shared anonymously with other researchers.

Data Protection Statement

The data controller for this project will be the University of Hull. The University will process your personal data for the purpose of the research outlined above. The legal basis for processing your personal data for research purposes under GDPR is a 'task in the public interest' You can provide your consent for the use of your personal data in this study by completing the consent form that has been provided to you. Information about how the University of Hull processes your data can be found at https://www.hull.ac.uk/choose-hull/university-and-region/key-documents/data-protection.aspx

You have the right to access information held about you. Your right of access can be exercised in accordance with the General Data Protection Regulation. You also have other rights including rights of correction, erasure, objection, and data portability. Questions, comments and requests about your personal data can also be sent to the University of Hull Information Compliance Manager Mr Luke Thompson [dataprotection@hull.ac.uk]. If you wish to lodge a complaint with the Information Commissioner's Office, please visit www.ico.org.uk.

What if I change my mind about taking part?

You are free withdraw at any point of the study without having to give a reason. Withdrawing from the study will not affect you in any way. You are able to withdraw your data from the study up until you leave the laboratory, after which the withdrawal of data will no longer be possible, as no personal identifiable information is stored with the data and consequently it will not be possible to trace your data to you. If you choose to withdraw from the study, we will not retain any information given thus far.

What will happen to the results of the study?

The results of the study may be disseminating in research conferences and journal publications.

Who has reviewed this study?

Research studies are reviewed by an independent group of people, called a Research Ethics Committee, to protect your interests. This study has been reviewed and been approved by **the Faculty of Health Sciences Ethics Committee, University of Hull.**

Who should I contact for further information?

If you have any questions or require more information about this study, please contact me or the research supervisor using the following contact details:

Sam Cowling: s.cowling-2019@hull.ac.uk

Dr David Smith: d.r.smith@hull.ac.uk

What if I have further questions, or if something goes wrong?

If you wish to make a complaint about the conduct of the study, you can contact the University of Hull using the details below for further advice and information:

In the first instance please contact Dr David Smith: d.r.smith@hull.ac.uk

Alternatively, please contact registrar@hull.ac.uk

THANK YOU FOR READING THIS INFORMATION SHEET AND FOR CONSIDERING TAKING PART IN THIS RESEARCH.

Appendix D – Informed consent form

UNIVERSITY
OF HULL

Version 1. Date: 16/12/2019

CONSENT FORM

Title of study: Perceptual and cognitive functioning as a function of personality

Name of Researchers: Sam Cowling, Dr David Smith

Please tick box

1. I confirm that I have read the information sheet dated 16/12/2019 version 1.0 for the above study. I have had the opportunity to consider the information, ask questions and have had any questions answered satisfactorily. ☐
2. I understand that my participation is voluntary and that I am free to withdraw at any time without giving any reason. However, after I have left the laboratory after the experimental session then I will be unable to withdraw my data because it will not be possible to identify my data. ☐
3. I understand that the research data, which will be anonymised (not linked to me), will be retained by the researchers and may be shared with others and publicly disseminated to support other research in the future. ☐
4. I understand that my personal data will be kept securely in accordance with data protection guidelines and will only be available to the immediate research team. ☐
5. I give permission for the collection and use of my data to answer the research question in this study. ☐
6. I agree to take part in the above study. ☐

______________________ ______________________ ______________________________

Name of Participant Date Signature

_____________________ _____________________ ____________________________

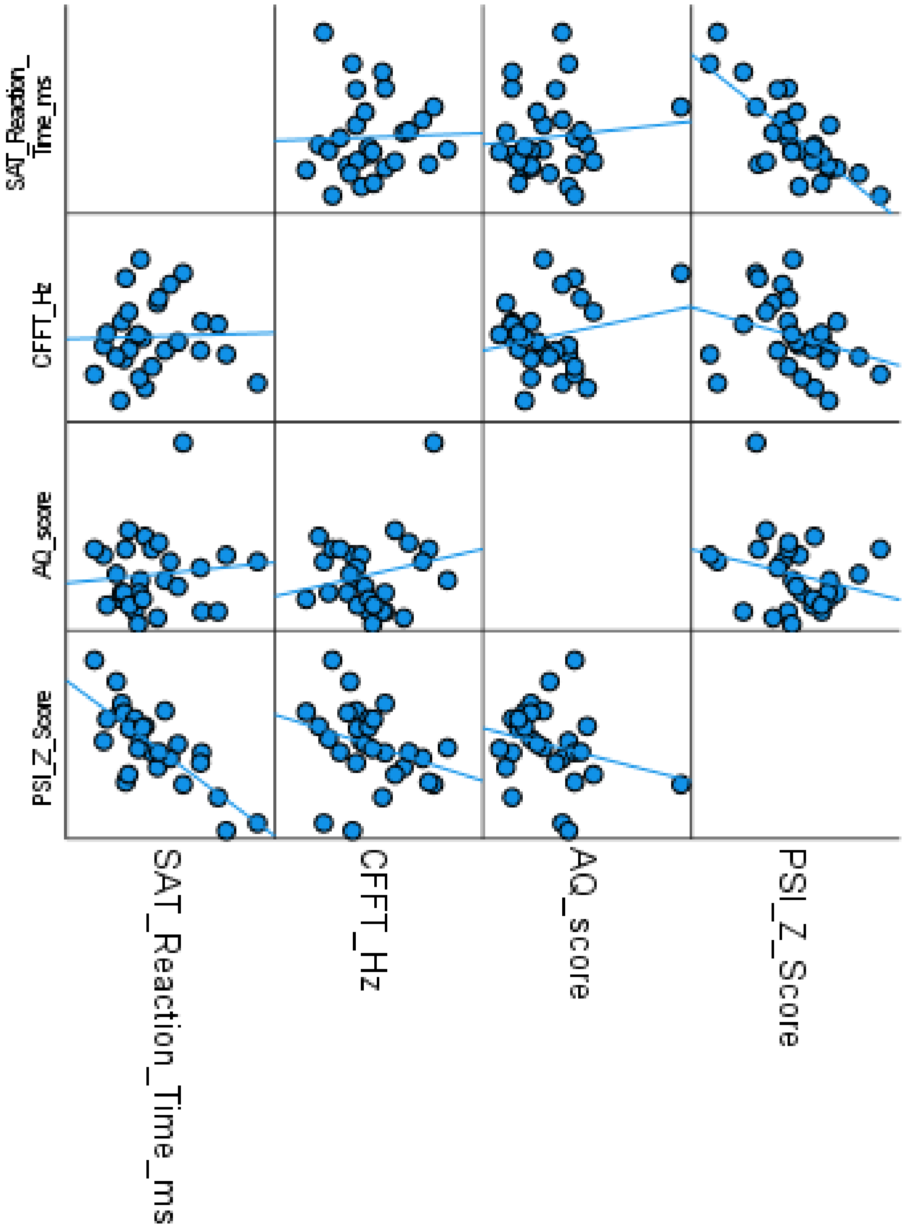
Name of Person Date Signature

taking consent

Appendix E – Matrix Scatterplot

Figure 7

Matrix scatterplot between all main covariables with regression lines



Note. Each data point represents one participant.

Appendix F – SPSS Outputs

Regression

Descriptive Statistics

	Mean	Std. Deviation	N
CFFT	31.3921	4.79054	28
SAT_RT_ms	1169.5611	295.53650	28
AQ	18.93	5.969	28
Wais_PSI	.0000	.81808	28

Correlations

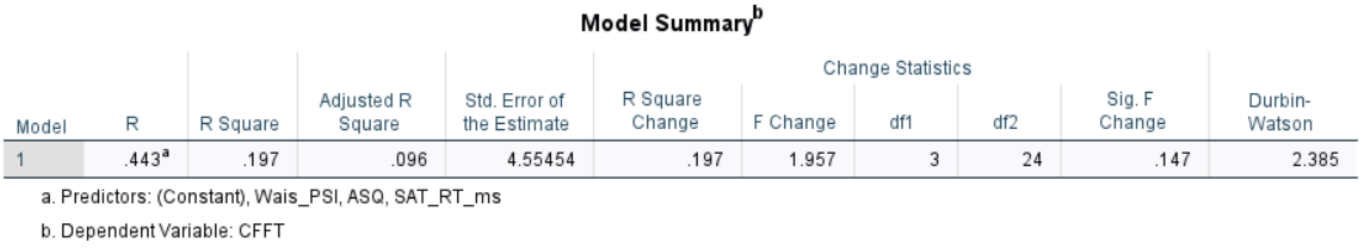
		CFFT	SAT_RT_ms	AQ	Wais_PSI
Pearson Correlation	CFFT	1.000	.033	.219	-.299
	SAT_RT_ms	.033	1.000	.104	-.770
	AQ	.219	.104	1.000	-.248
	Wais_PSI	-.299	-.770	-.248	1.000
Sig. (1-tailed)	CFFT	.	.434	.131	.061
	SAT_RT_ms	.434	.	.299	.000
	AQ	.131	.299	.	.101
	Wais_PSI	.061	.000	.101	.
N	CFFT	28	28	28	28
	SAT_RT_ms	28	28	28	28
	AQ	28	28	28	28
	Wais_PSI	28	28	28	28

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Wais_PSI, AQ, SAT_RT_ms[b]	.	Enter

a. Dependent Variable: CFFT

b. All requested variables entered.



Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.443[a]	.197	.096	4.55454	.197	1.957	3	24	.147	2.385

a. Predictors: (Constant), Wais_PSI, ASQ, SAT_RT_ms

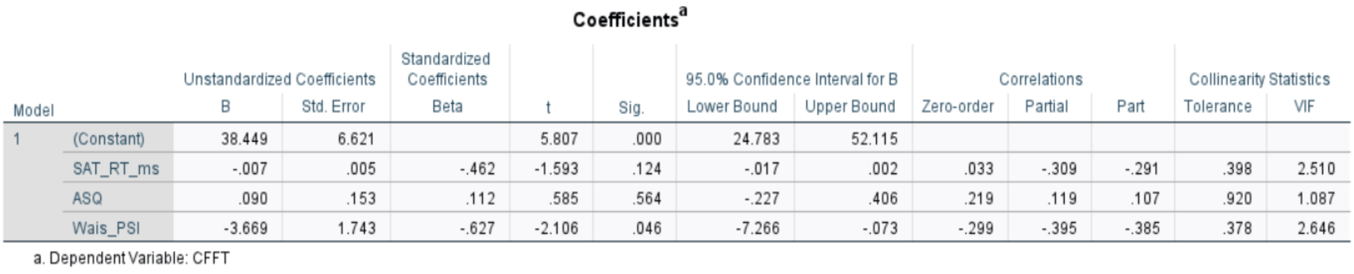
b. Dependent Variable: CFFT

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	121.779	3	40.593	1.957	.147[b]
	Residual	497.853	24	20.744		
	Total	619.632	27			

a. Dependent Variable: CFFT

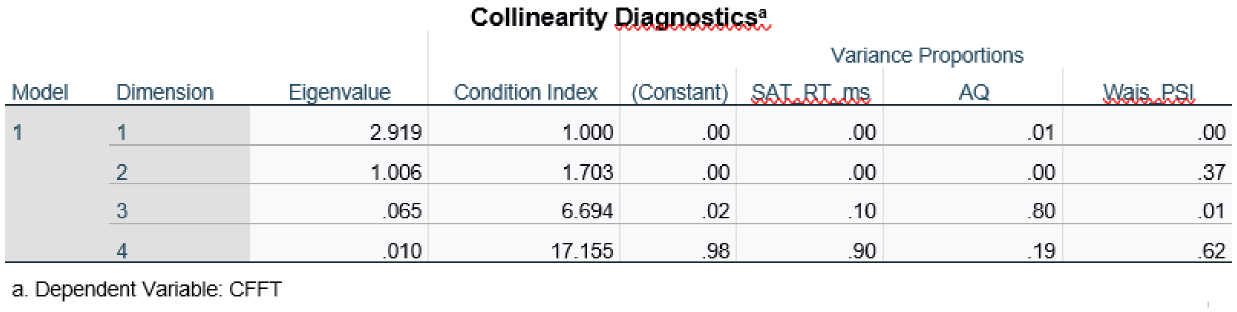
b. Predictors: (Constant), Wais_PSI, AQ, SAT_RT_ms



Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	38.449	6.621		5.807	.000	24.783	52.115					
	SAT_RT_ms	-.007	.005	-.462	-1.593	.124	-.017	.002	.033	-.309	-.291	.398	2.510
	ASQ	.090	.153	.112	.585	.564	-.227	.406	.219	.119	.107	.920	1.087
	Wais_PSI	-3.669	1.743	-.627	-2.106	.046	-7.266	-.073	-.299	-.395	-.385	.378	2.646

a. Dependent Variable: CFFT



Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions			
				(Constant)	SAT_RT_ms	AQ	Wais_PSI
1	1	2.919	1.000	.00	.00	.01	.00
	2	1.006	1.703	.00	.00	.00	.37
	3	.065	6.694	.02	.10	.80	.01
	4	.010	17.155	.98	.90	.19	.62

a. Dependent Variable: CFFT

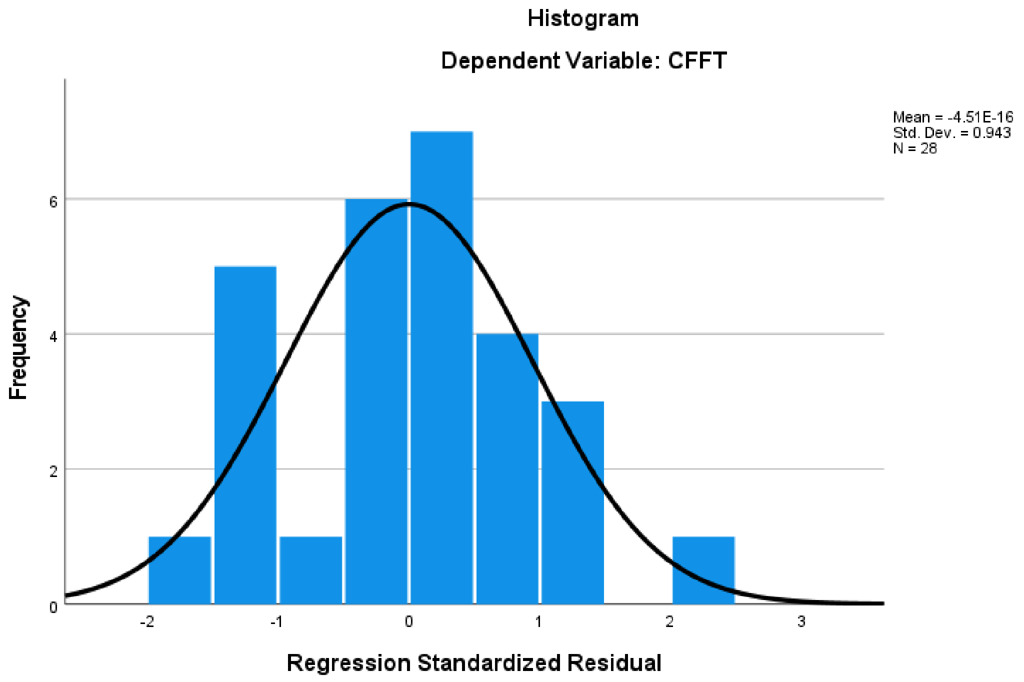
Residuals Statistics[a]

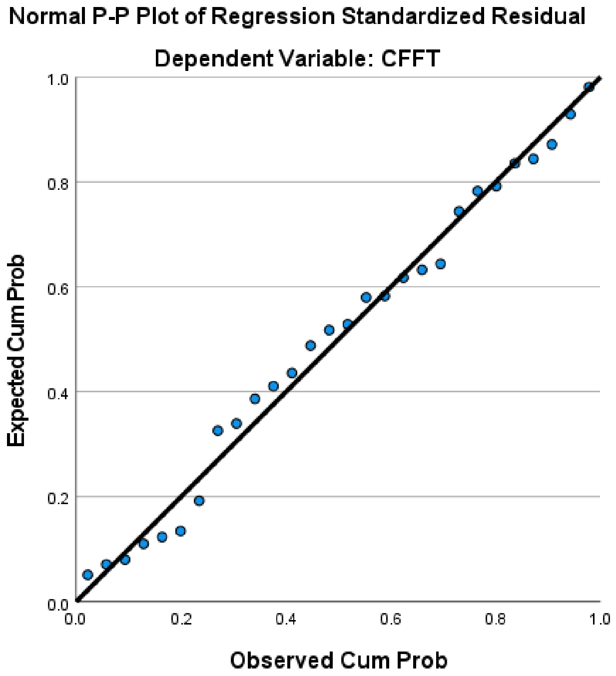
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	27.9598	36.1812	31.3921	2.12376	28
Std. Predicted Value	-1.616	2.255	.000	1.000	28
Standard Error of Predicted Value	.981	3.238	1.634	.551	28

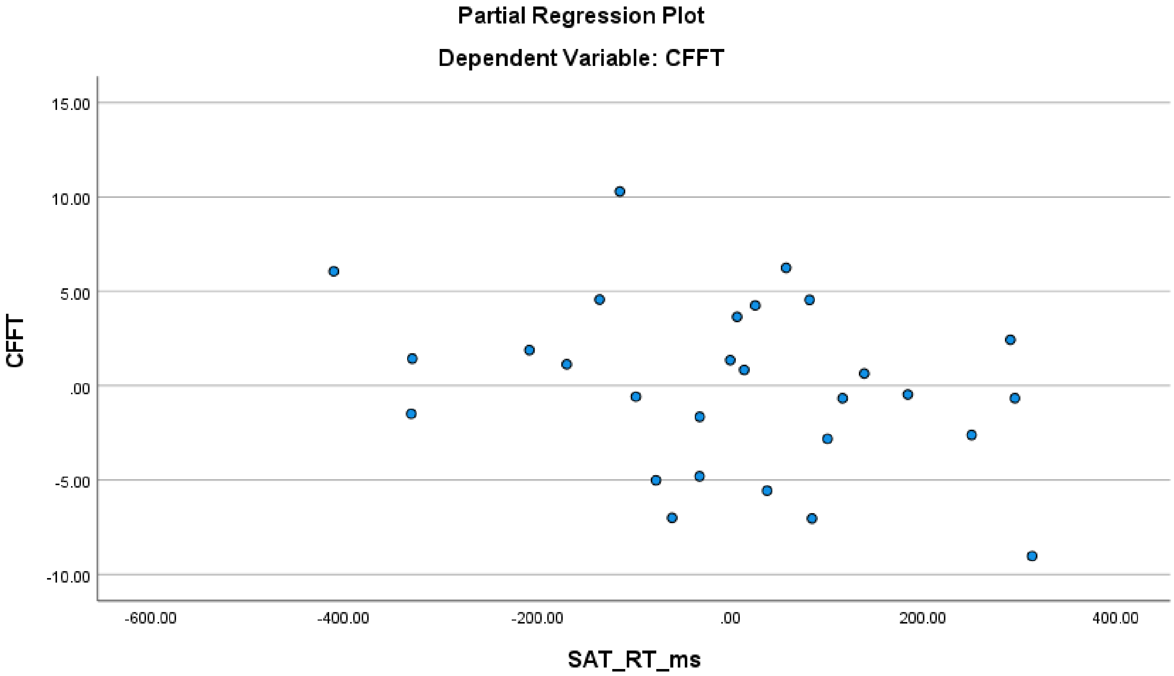
Adjusted Predicted Value	27.6712	35.9706	31.3267	2.26225	28
Residual	-7.45355	9.43846	.00000	4.29406	28
Std. Residual	-1.637	2.072	.000	.943	28
Stud. Residual	-1.747	2.127	.005	1.026	28
Deleted Residual	-9.47526	10.43980	.06546	5.18308	28
Stud. Deleted Residual	-1.831	2.312	.006	1.060	28
Mahal. Distance	.288	12.681	2.893	2.765	28
Cook's Distance	.000	.664	.058	.134	28
Centered Leverage Value	.011	.470	.107	.102	28

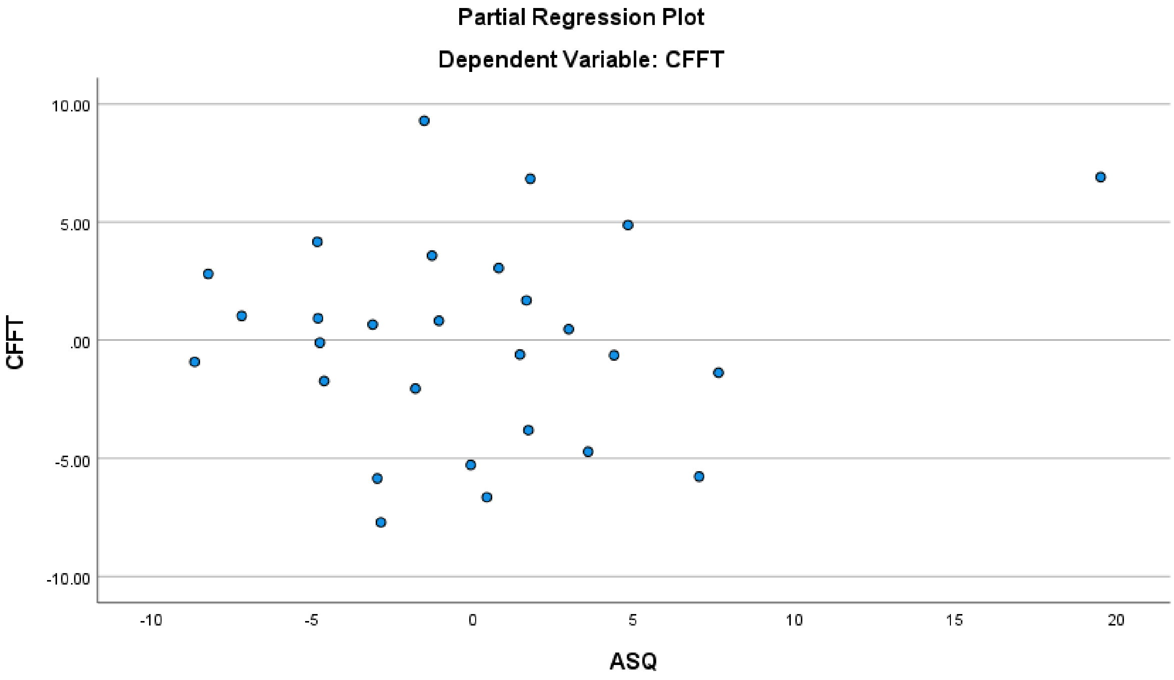
a. Dependent Variable: CFFT

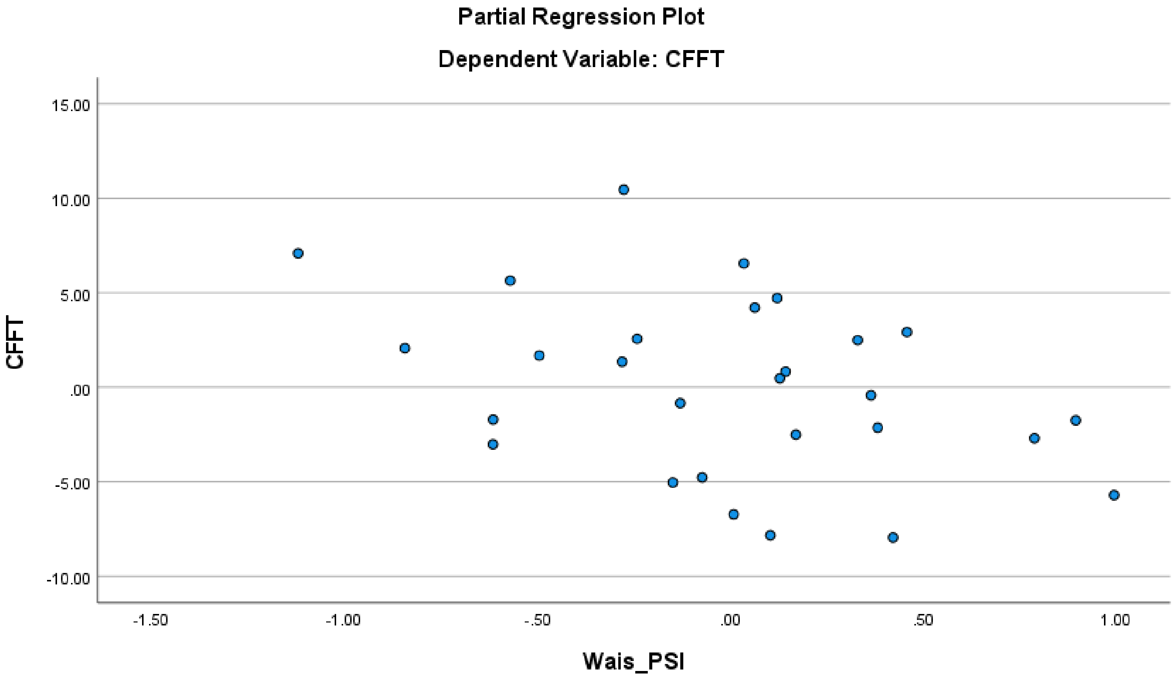
Charts




Normal P-P Plot of Regression Standardized Residual
Dependent Variable: CFFT
Expected Cum Prob
Observed Cum Prob
0.0
0.2
0.4
0.6
0.8
1.0


Partial Regression Plot
Dependent Variable: CFFT
CFFT
15.00
10.00
5.00
.00
-5.00
-10.00
-600.00
-400.00
-200.00
.00
200.00
400.00
SAT_RT_ms

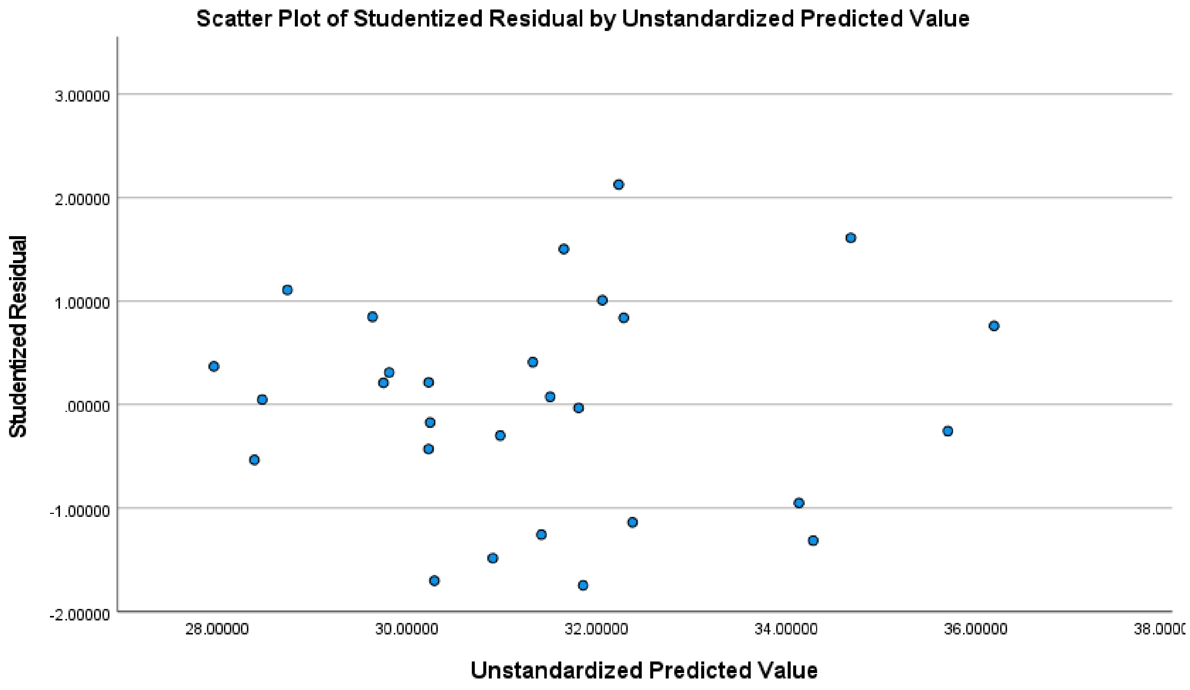




```
* Chart Builder.
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=PRE_1 SRE_1 MISSING=LISTWISE
REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE
  /FITLINE TOTAL=NO SUBGROUP=NO.
BEGIN GPL
```

```
  SOURCE: s=userSource(id("graphdataset"))
  DATA: PRE_1=col(source(s), name("PRE_1"))
  DATA: SRE_1=col(source(s), name("SRE_1"))
  GUIDE: axis(dim(1), label("Unstandardized Predicted Value"))
  GUIDE: axis(dim(2), label("Studentized Residual"))
  GUIDE: text.title(label("Scatter Plot of Studentized Residual by Unstandardized
Predicted Value"))
  ELEMENT: point(position(PRE_1*SRE_1))
END GPL.
```

GGraph



```
PPLOT
  /VARIABLES=SRE_1
  /NOLOG
  /NOSTANDARDIZE
  /TYPE=Q-Q
  /FRACTION=BLOM
  /TIES=MEAN
  /DIST=NORMAL.
```

PPlot

Model Description

Model Name		MOD_1
Series or Sequence	1	Studentized Residual
Transformation		None
Non-Seasonal Differencing		0
Seasonal Differencing		0
Length of Seasonal Period		No periodicity
Standardization		Not applied
Distribution	Type	Normal
	Location	estimated
	Scale	estimated
Fractional Rank Estimation Method		Blom's
Rank Assigned to Ties		Mean rank of tied values

Applying the model specifications from MOD_1

Case Processing Summary

		Studentized Residual
Series or Sequence Length		28
Number of Missing Values in the Plot	User-Missing	0
	System-Missing	0

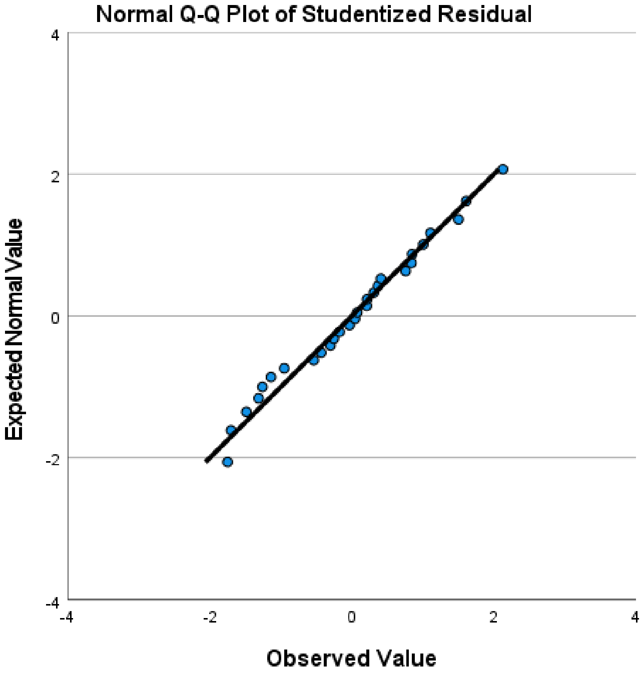
The cases are unweighted.

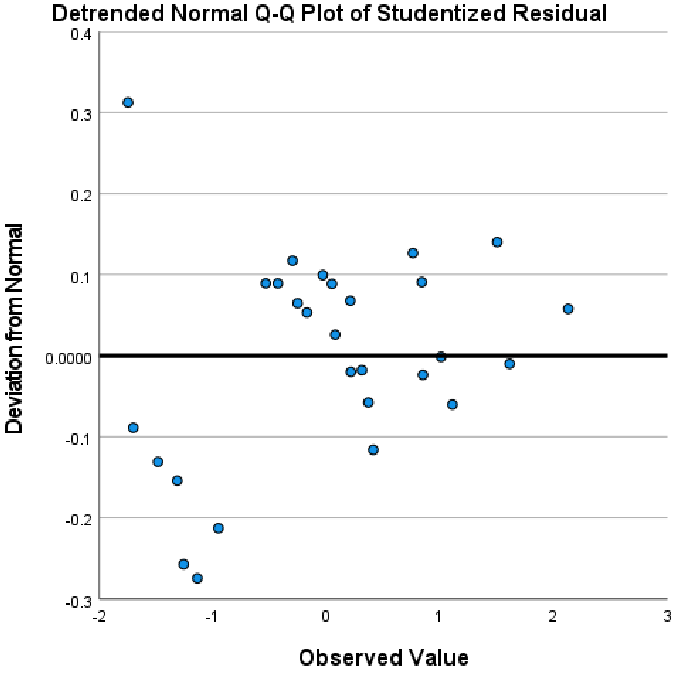
Estimated Distribution Parameters

		Studentized Residual
Normal Distribution	Location	.0047618
	Scale	1.02626891

The cases are unweighted.

Studentized Residual





Regression

Descriptive Statistics

	Mean	Std. Deviation	N
AQ	18.15	4.391	27
CFFT	31.0794	4.58136	27
SAT_RT_ms	1161.1982	297.77093	27
Wais_PSI	.0311	.81662	27

Correlations

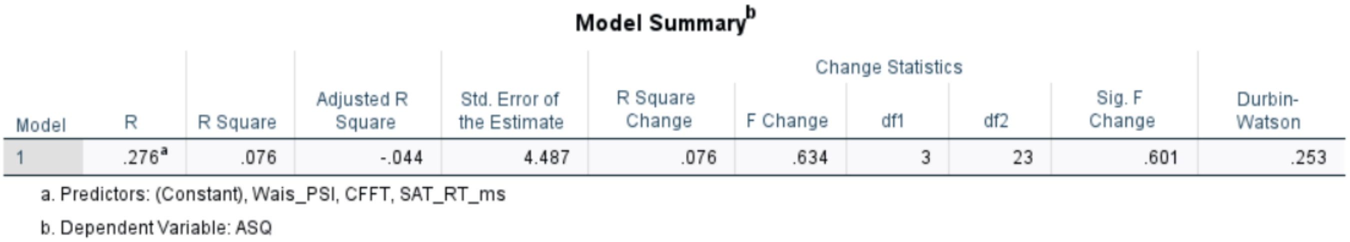
		AQ	CFFT	SAT_RT_ms	Wais_PSI
Pearson Correlation	AQ	1.000	-.029	.001	-.154
	CFFT	-.029	1.000	-.020	-.249
	SAT_RT_ms	.001	-.020	1.000	-.764
	Wais_PSI	-.154	-.249	-.764	1.000
Sig. (1-tailed)	AQ	.	.442	.499	.221
	CFFT	.442	.	.460	.105
	SAT_RT_ms	.499	.460	.	.000
	Wais_PSI	.221	.105	.000	.
N	AQ	27	27	27	27
	CFFT	27	27	27	27
	SAT_RT_ms	27	27	27	27
	Wais_PSI	27	27	27	27

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Wais_PSI, CFFT, SAT_RT_ms[b]	.	Enter

a. Dependent Variable: AQ

b. All requested variables entered.



Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	.276[a]	.076	-.044	4.487	.076	.634	3	23	.601	.253

a. Predictors: (Constant), Wais_PSI, CFFT, SAT_RT_ms

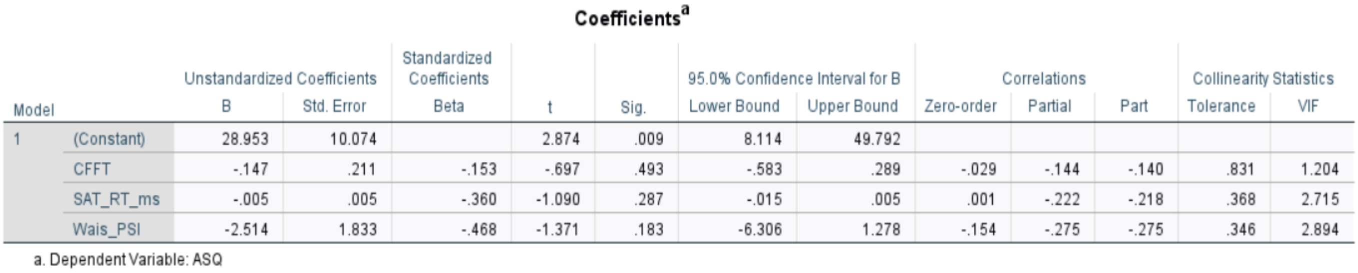
b. Dependent Variable: ASQ

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	38.303	3	12.768	.634	.601[b]
	Residual	463.105	23	20.135		
	Total	501.407	26			

a. Dependent Variable: AQ

b. Predictors: (Constant), Wais_PSI, CFFT, SAT_RT_ms



Coefficients[a]

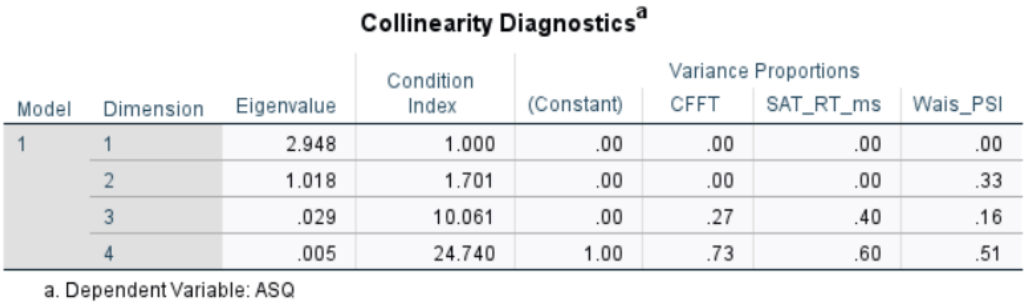
Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
		B	Std. Error	Beta			Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
1	(Constant)	28.953	10.074		2.874	.009	8.114	49.792					
	CFFT	-.147	.211	-.153	-.697	.493	-.583	.289	-.029	-.144	-.140	.831	1.204
	SAT_RT_ms	-.005	.005	-.360	-1.090	.287	-.015	.005	.001	-.222	-.218	.368	2.715
	Wais_PSI	-2.514	1.833	-.468	-1.371	.183	-6.306	1.278	-.154	-.275	-.275	.346	2.894

a. Dependent Variable: ASQ

Coefficient Correlations[a]

Model			Wais_PSI	CFFT	SAT_RT_ms
1	Correlations	Wais_PSI	1.000	.411	.795
		CFFT	.411	1.000	.338
		SAT_RT_ms	.795	.338	1.000
	Covariances	Wais_PSI	3.360	.159	.007
		CFFT	.159	.044	.000
		SAT_RT_ms	.007	.000	2.371E-5

a. Dependent Variable: AQ



Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions			
				(Constant)	CFFT	SAT_RT_ms	Wais_PSI
1	1	2.948	1.000	.00	.00	.00	.00
	2	1.018	1.701	.00	.00	.00	.33
	3	.029	10.061	.00	.27	.40	.16
	4	.005	24.740	1.00	.73	.60	.51

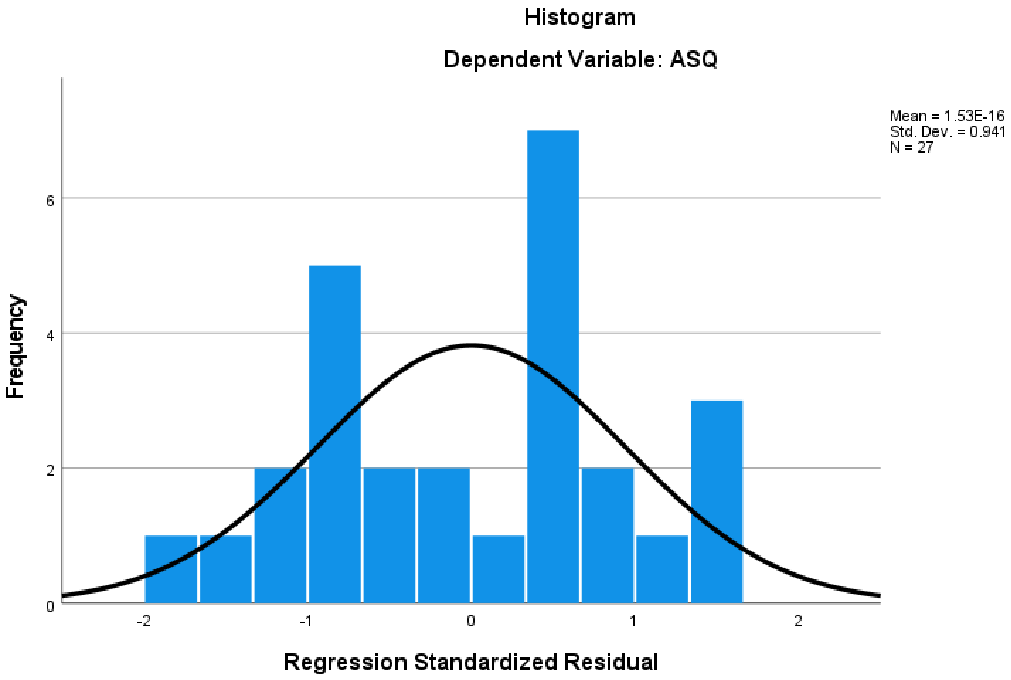
a. Dependent Variable: ASQ

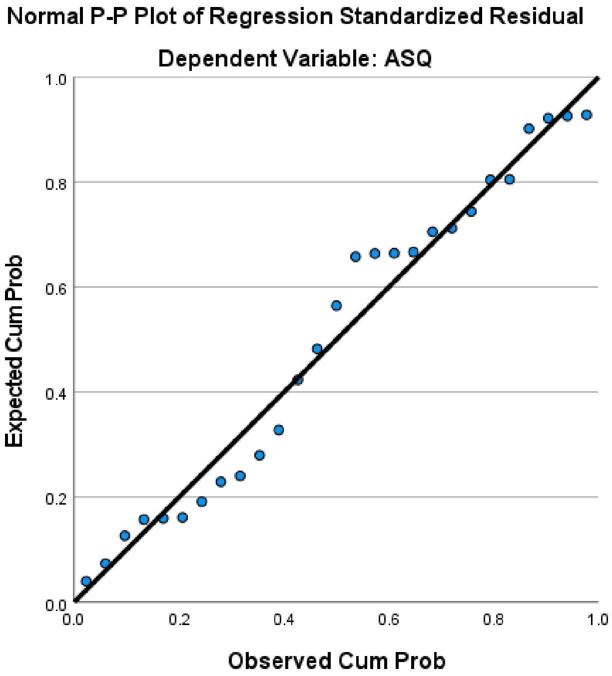
Residuals Statistics[a]

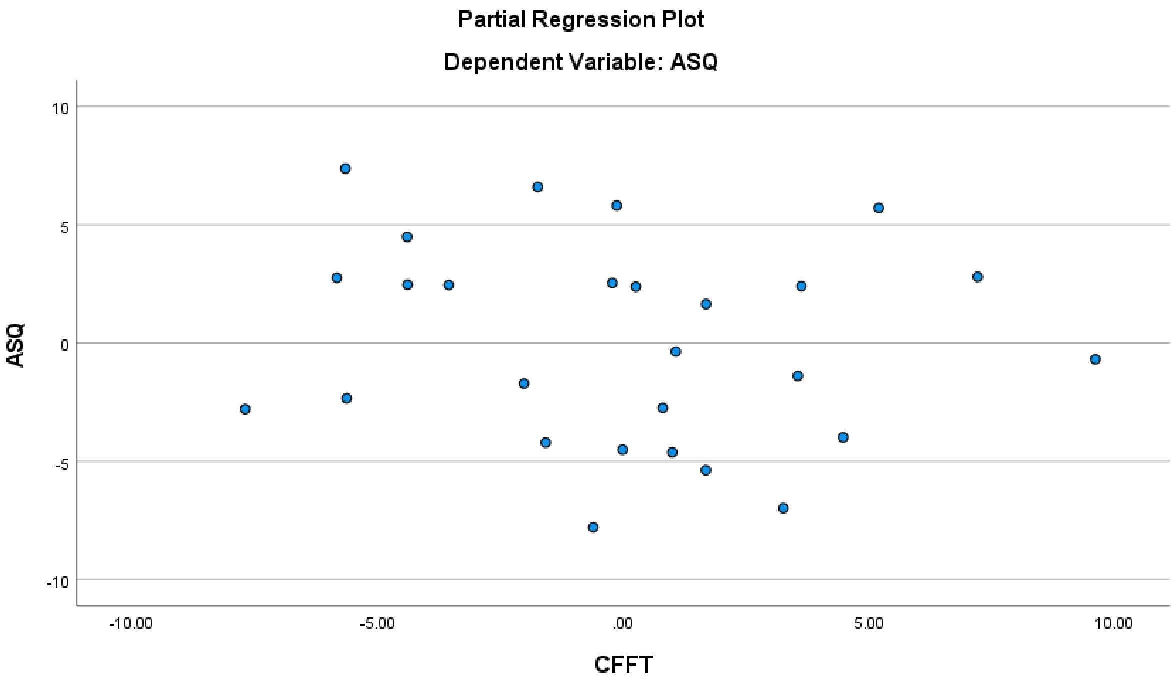
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	16.10	20.20	18.15	1.214	27
Std. Predicted Value	-1.685	1.692	.000	1.000	27
Standard Error of Predicted Value	.965	2.774	1.663	.473	27
Adjusted Predicted Value	14.75	19.87	17.95	1.326	27
Residual	-7.884	6.551	.000	4.220	27
Std. Residual	-1.757	1.460	.000	.941	27
Stud. Residual	-1.809	1.613	.020	1.009	27
Deleted Residual	-8.360	8.253	.200	4.876	27
Stud. Deleted Residual	-1.911	1.676	.020	1.030	27
Mahal. Distance	.240	8.976	2.889	2.193	27
Cook's Distance	.000	.195	.039	.043	27
Centered Leverage Value	.009	.345	.111	.084	27

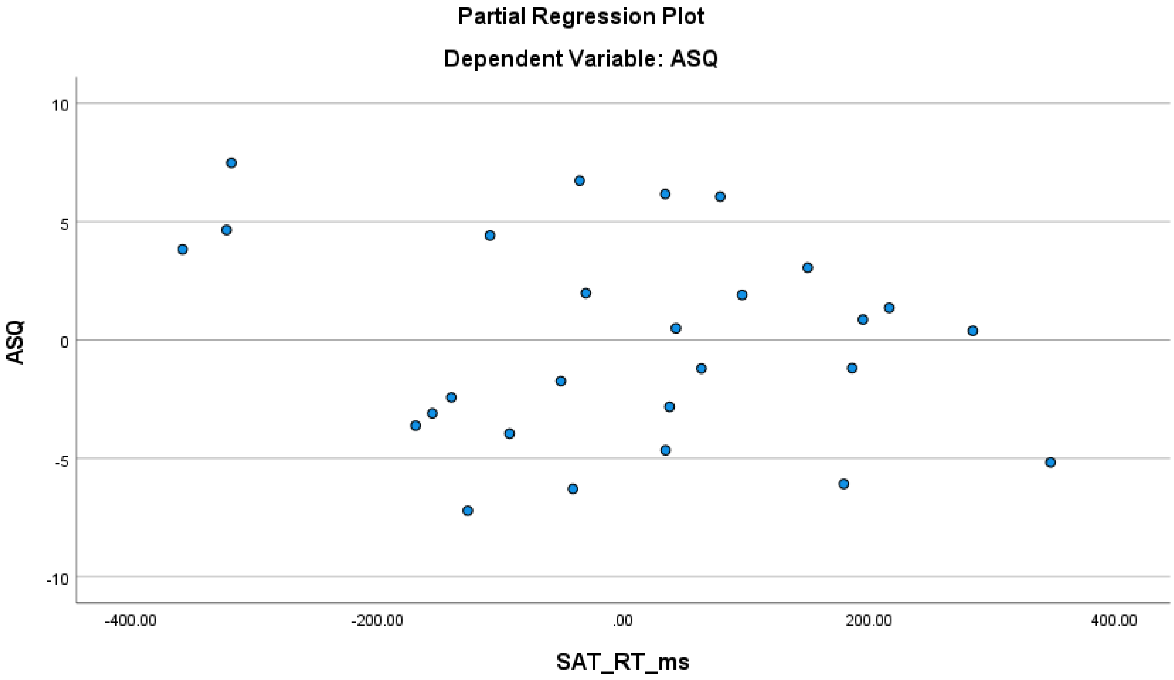
a. Dependent Variable: AQ

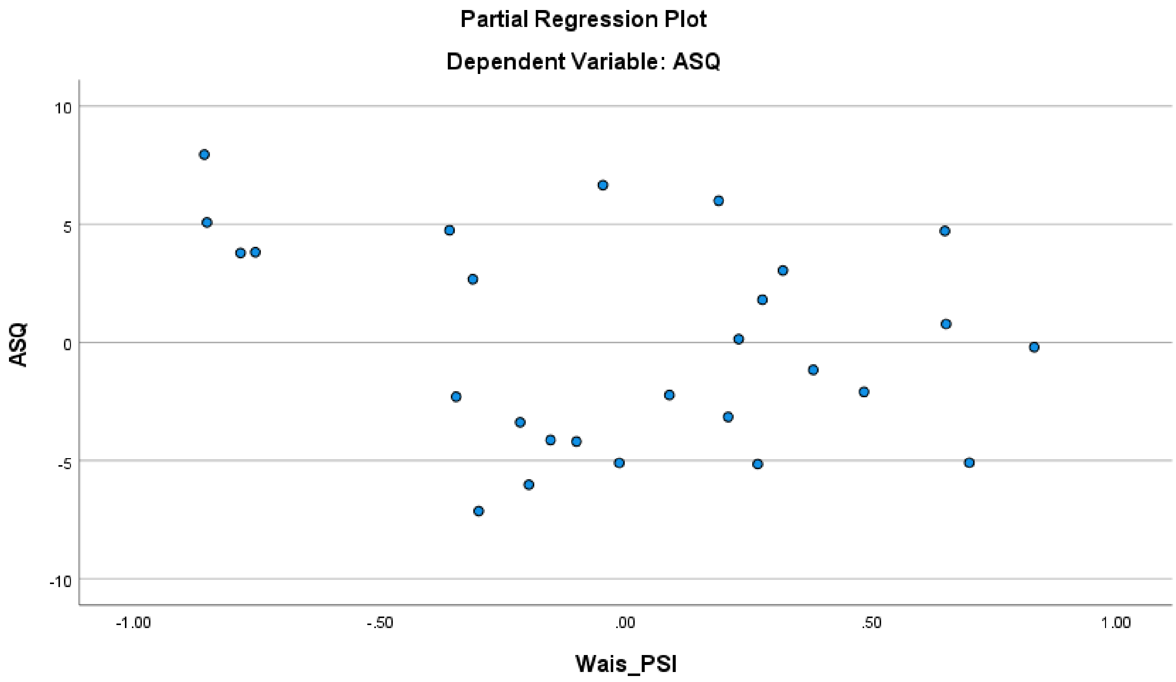
Charts


Histogram
Dependent Variable: ASQ
Mean = 1.53E-16
Std. Dev. = 0.941
N = 27
Frequency
0
2
4
6
-2
-1
0
1
2
Regression Standardized Residual


Normal P-P Plot of Regression Standardized Residual
Dependent Variable: ASQ
Expected Cum Prob
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.2
0.4
0.6
0.8
1.0
Observed Cum Prob

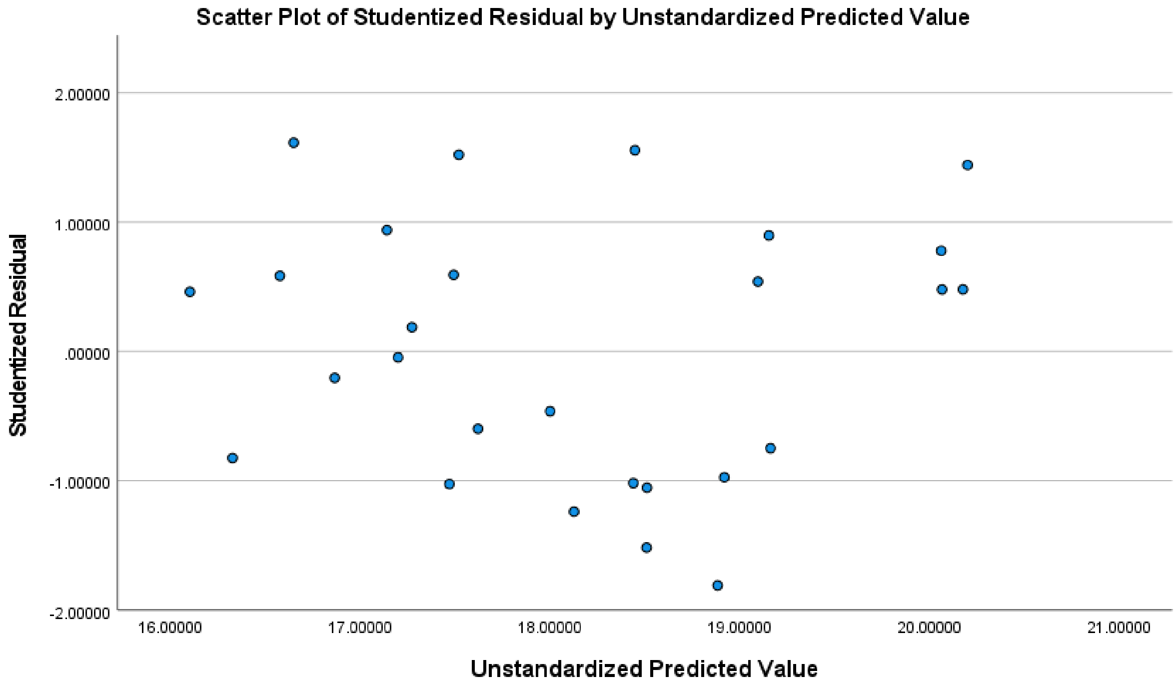

Partial Regression Plot
Dependent Variable: ASQ
ASQ
10
5
0
-5
-10
-10.00
-5.00
.00
5.00
10.00
CFFT


Partial Regression Plot
Dependent Variable: ASQ
ASQ
10
5
0
-5
-10
-400.00
-200.00
.00
200.00
400.00
SAT_RT_ms



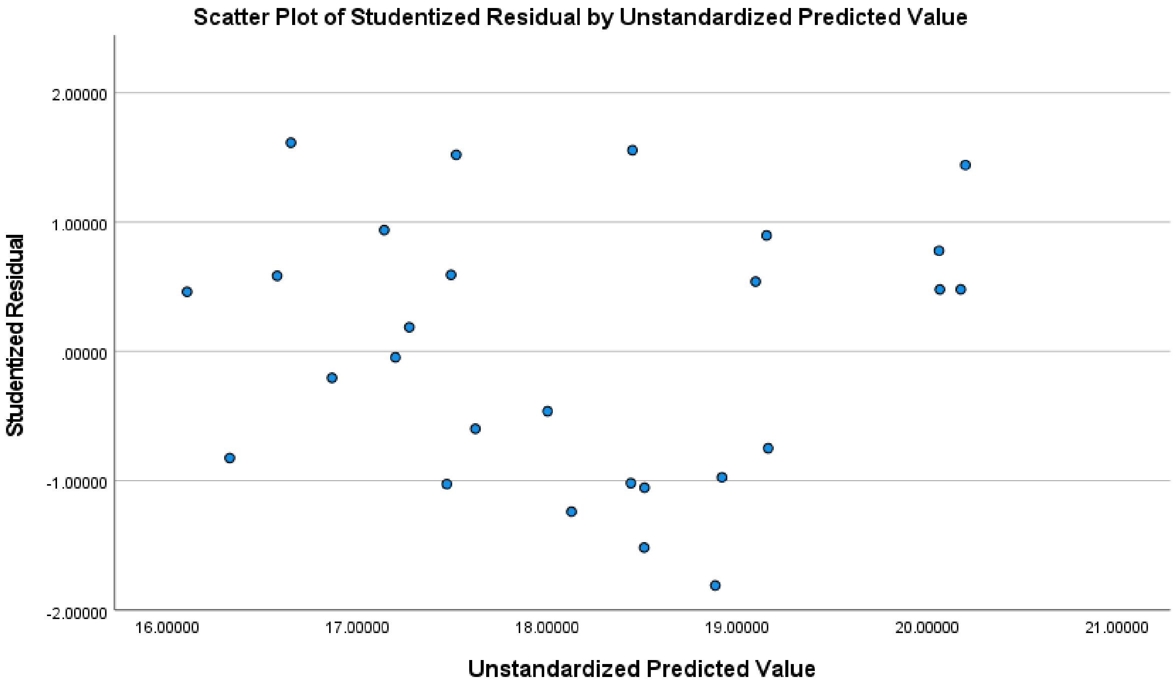
```
* Chart Builder.
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=PRE_2 SRE_2 MISSING=LISTWISE
REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE
  /FITLINE TOTAL=NO SUBGROUP=NO.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: PRE_2=col(source(s), name("PRE_2"))
  DATA: SRE_2=col(source(s), name("SRE_2"))
  GUIDE: axis(dim(1), label("Unstandardized Predicted Value"))
  GUIDE: axis(dim(2), label("Studentized Residual"))
  GUIDE: text.title(label("Scatter Plot of Studentized Residual by Unstandardized
Predicted Value"))
  ELEMENT: point(position(PRE_2*SRE_2))
END GPL.
```

GGraph



```
* Chart Builder.
GGRAPH
  /GRAPHDATASET NAME="graphdataset" VARIABLES=PRE_2 SRE_2 MISSING=LISTWISE
REPORTMISSING=NO
  /GRAPHSPEC SOURCE=INLINE
  /FITLINE TOTAL=NO SUBGROUP=NO.
BEGIN GPL
  SOURCE: s=userSource(id("graphdataset"))
  DATA: PRE_2=col(source(s), name("PRE_2"))
  DATA: SRE_2=col(source(s), name("SRE_2"))
  GUIDE: axis(dim(1), label("Unstandardized Predicted Value"))
  GUIDE: axis(dim(2), label("Studentized Residual"))
  GUIDE: text.title(label("Scatter Plot of Studentized Residual by Unstandardized
Predicted Value"))
  ELEMENT: point(position(PRE_2*SRE_2))
END GPL.
```

GGraph



```
SORT CASES BY SRE_2 (D).
SORT CASES BY SDR_2 (D).
SORT CASES BY SDR_2 (A).
SORT CASES BY LEV_2 (D).
SORT CASES BY LEV_2 (A).
SORT CASES BY COO_2 (D).
SORT CASES BY COO_2 (A).
PPLOT
  /VARIABLES=SRE_2
  /NOLOG
  /NOSTANDARDIZE
  /TYPE=Q-Q
  /FRACTION=BLOM
  /TIES=MEAN
  /DIST=NORMAL.
```

PPlot

Model Description

Model Name		MOD_1
Series or Sequence	1	Studentized Residual
Transformation		None
Non-Seasonal Differencing		0
Seasonal Differencing		0
Length of Seasonal Period		No periodicity

Standardization		Not applied
Distribution	Type	Normal
	Location	estimated
	Scale	estimated
Fractional Rank Estimation Method		Blom's
Rank Assigned to Ties		Mean rank of tied values

Applying the model specifications from MOD_1

Case Processing Summary

		Studentized Residual
Series or Sequence Length		27
Number of Missing Values in the Plot	User-Missing	0
	System-Missing	0

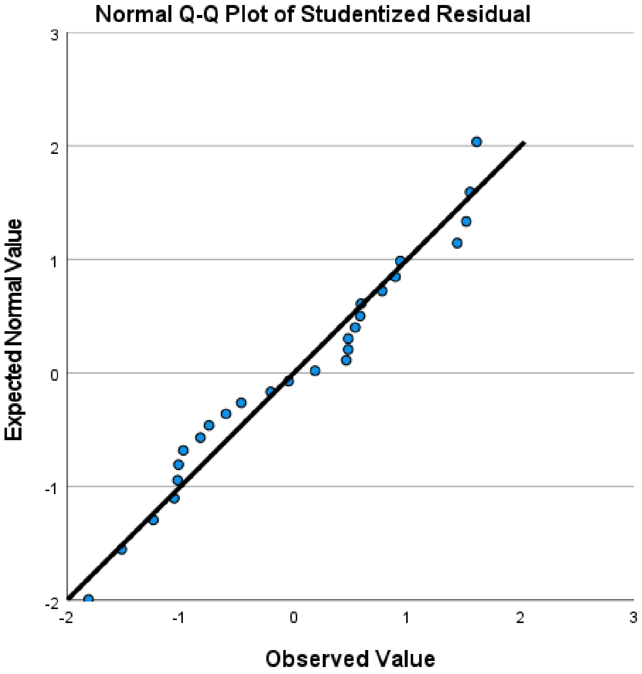
The cases are unweighted.

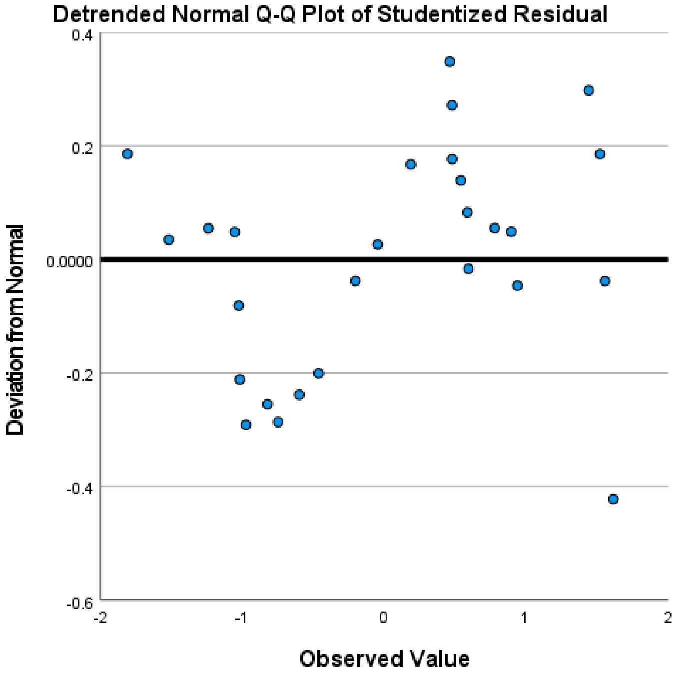
Estimated Distribution Parameters

		Studentized Residual
Normal Distribution	Location	.0202399
	Scale	1.00940026

The cases are unweighted.

Studentized Residual


Normal Q-Q Plot of Studentized Residual
Expected Normal Value
Observed Value
3
2
1
0
-1
-2
-2
-1
0
1
2
3


Detrended Normal Q-Q Plot of Studentized Residual
Deviation from Normal
Observed Value
0.4
0.2
0.0000
-0.2
-0.4
-0.6
-2
-1
0
1
2