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Critical Flicker Fusion Predicts Executive Function in Younger and Older Adults

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Abstract

Critical flicker fusion (CFF), a measure of visual processing speed, has often been regarded as a basic metric underlying a number of higher cognitive functions. To test this, we measured CFF, global cognition, and several cognitive subdomains. Because age is a strong covariate for most of these variables, both younger ($n = 72$) and older ($n = 57$) subjects were measured. Consistent with expectations, age was inversely related to CFF and performance on all of the cognitive measures except for visual memory. In contrast, age-adjusted CFF thresholds were only positively related to executive function. Results showed that CFF predicted executive function across both age groups and accounted for unique variance in performance above and beyond age and global cognitive status. The current findings suggest that CFF may be a unique predictor of executive dysfunction.

Keywords: Critical flicker fusion; CFF; Elderly/geriatrics/aging; Executive functions; Assessment

Introduction

Sensory function, particularly in the visual domain, has long been studied in the context of cognitive aging. Early work in this area linked visual acuity to general intelligence and reasoning (e.g., Lindenberger & Baltes, 1994), memory (e.g., Lövdén & Wahlin, 2005), and executive function and inhibition in older adults (Lövdén & Wahlin, 2005). Common explanations for this connection are that sensory failure in older individuals is both a gateway to cognitive decline (e.g., by reducing informational input) and/or a biomarker for deleterious change in the brain (see Chang et al., 2014). Recently, other measures of visual performance have gained popularity as research tools due to criticisms about the sensitivity of visual acuity to changes in cognitive performance. This is especially true given the rise of visual acuity deficits and its association with educational attainment (Williams & Hammond, 2014).

Contrast sensitivity (CS) is a visual measure that represents the ability to distinguish between an object and its background. Like visual acuity, CS can be measured easily using standardized clinical instruments such as the Pelli–Robson chart (Pelli, Robson, & Wilkins, 1988), Melbourne Edge Test (Haymes & Chen, 2004), or the Visual Contrast Test System (Scialfa, Adams, & Giovanetto, 1991). Research using these measures has shown that CS predicts cognitive processes including global cognition (Risacher et al., 2013; Skeel, Schutte, van Voorst, & Nagra, 2006), memory (Anstey, Butterworth, Borzycki, & Andrews, 2006; Risacher et al., 2013), processing speed (e.g., Anstey et al., 2006), and executive function (Cronin-Golomb, Corkin, & Growdon, 1995). Such relations may stem from the fact that, unlike standard Snellen acuity (driven mostly by the refractive state of the eye), measuring the full CS function provides more information about the integrity of the entire visual pathway. Additionally, CS predicts reductions in cognitive performance even when visual acuity remains intact (e.g., Wood et al., 2009, 2010). However, the effects of CS on cognitive performance may not be consistent across the lifespan. Although degraded CS negatively affects speeded performance even in a group of younger adults (Wood et al., 2009), one study found that simulated visual impairment negatively affected cognitive performance to a greater degree in a group of older versus younger adults (Wood et al., 2010).

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Although changes in spatial vision, when well characterized, do appear to predict age-related changes in at least some aspects of cognitive performance, perhaps an even better measure is processing speed (Salthouse, 2000). Previous literature supports processing speed as a crucial variable underlying performance across multiple cognitive domains, including episodic memory, working memory, and reasoning (see Salthouse, 1996 for review) as well as executive functions, including inhibition, updating, and shifting (e.g., Albinet, Boucard, Bouquet, & Audiffren, 2012).

Processing speed can be measured in a multitude of ways that include simple motor reaction time, judgment reaction time, etc. and can be measured in different sensory modalities. Visual processing speed is one of the most common modalities tested and can be assessed relatively simply (Wooten, Renzi, Moore, & Hammond, 2010). Critical flicker fusion (CFF) thresholds, for example, are measures of the highest average frequency at which an individual can perceive a flickering stimulus. They represent the highest frequency point of the temporal CS function (100% modulation) and appear to be strongly driven not just by the eye, but also processes within the brain itself (Curran, Hindmarch, Wattis, & Shillingford, 1990; Curran & Wattis, 1998; Nardella et al., 2014). Additionally, CFF performance can be negatively affected by tumors and lesions in all four lobes of the brain (Curran et al., 1990; Curran & Wattis, 1998). Thus, CFF is hypothesized to be a measure of overall neural integrity and firing rate.

CFF has been shown to be a useful tool in cognitive aging research because it is sensitive to aging and disease processes; older adults and individuals with Alzheimer's disease show decrements in performance (Curran et al., 1990; Renzi & Hammond, 2010; Wooten et al., 2010). CFF has also been used in pharmacological research because it is sensitive to the manipulations of drugs; stimulants can increase and depressants can decrease performance (Curran & Wattis, 1998; Renzi & Hammond, 2010). Recent studies have shown that dietary supplementation (focusing on the plant pigments, xanthophylls, found in retina and brain) can improve CFF thresholds of even younger adults when compared with placebos (Bovier and Hammond, 2015; Bovier, Renzi, & Hammond, 2014).

Several factors have limited the generalizability of CFF studies in the past. For example, stimuli composed of shorter wavelengths can be absorbed by the natural yellow intraocular filters of the eye (the aging crystalline lens and macular pigment) and confound relations due to optical factors. If pupil size is not corrected, CFF will vary due to a reduction in luminance as opposed to actual processing speed (Rovamo and Raninen, 1988).

In the present study, these factors were controlled; CFF, global cognition, and several cognitive subdomains were measured in a sample of younger and older adults. Cognitive domains were chosen based on previous literature demonstrating the relation of sensory function to global cognition, as well as memory, processing speed, and aspects of executive function. We hypothesized that younger adults would perform better on all cognitive measures than older adults. We also predicted that individuals with higher CFF performance would score better on all cognitive measures than individuals with lower CFF performance. Finally, based on the differential age effects found by Wood and colleagues (2009, 2010), we hypothesized that age group (young vs. old) would moderate the relationship between CFF performance and cognition, such that older adults with higher CFF would retain significantly higher cognitive performance than older adults with lower CFF, while CFF would be less related to cognition in younger adults. In other words, the relation between CFF and cognition would increase with age.

Methods

Participants

Seventy-two younger adults (37 men and 35 women, average age 21.7 years) and 57 older adults (22 men and 35 women, average age 72.4 years) were recruited as part of a larger, ongoing study at the University of Georgia. Younger adults were primarily undergraduate and graduate students at the University of Georgia. Older adults were all community-dwelling individuals, with a mean education level of 16.5 years, indicating that most were college educated. General exclusionary criteria included history of ocular disease and corrected visual acuity worse than 20:60 (Snellen notation). Older adults were also excluded if they exhibited more than mild cognitive impairment, defined as a global rating score of >0.5 on the Clinical Dementia Rating scale (CDR; Morris, 1993). Data collection occurred across two visits. During the first visit, visual measures, including CFF, were acquired. During the second visit, cognitive measures were acquired for all participants; additionally, the CDR was collected for older adults only. All measures were administered by trained research assistants who presented standard instructional sets and answered questions. Participants received a small monetary compensation for their time. The study protocol was approved by the Institutional Review Board at the University of Georgia and informed consent was obtained from all participants.

Materials

Critical flicker fusion. CFF was measured using a custom-built, tabletop LED device. More detailed description of the device and validation process can be found in Wooten and colleagues (2010). Briefly, the stimulus was a circular, 1°, 660 nm, 20 nm half

bandpass (Nichia Corp., Mountville, PA) light that flickered at 100% modulation. The 1° stimulus was presented at the center of a 5.5°, 660 nm surround (average luminance, 25 cd/m^2). Participants viewed the stimulus through a 3-mm artificial pupil and maintained focus on a small (5′) fixation point at the center of the target.

CFF performance was calculated (using a method of limits, in 1 Hz intervals) as the average of three ascending trials (frequency of flicker was increased until the stimulus appeared fused) and three descending trials (frequency of flicker was decreased until the flickering was detected). Higher values (expressed in Hz) indicate better performance. Past studies using these conditions have shown CFF to be highly reliable (Cronbach's $\alpha = 0.95$; Hammond and Wooten, 2005; Wooten et al., 2010).

Cognitive measures. Performance on cognitive tasks was measured using the CNS-Vital Signs (CNS-VS) computerized cognitive battery. CNS-VS uses computerized adaptations of familiar neuropsychological tests and has been validated as a measure of cognitive performance (e.g., Gualtieri & Johnson, 2006). CNS-VS creates index scores for various cognitive domains based on performance on individual cognitive tasks, which are briefly described subsequently. These index scores were used in the statistical analyses. Further, we created a composite global cognitive variable by averaging scores across these indices.

Verbal memory is measured using a word list learning task with immediate and delayed recognition memory components. Similarly, visual memory is measured using a shape learning task with both immediate and delayed recognition memory components. Processing speed is measured using a symbol-digit coding task; participants complete as many items as possible in 2 min. Reasoning is measured using a matrix reasoning task; participants solved 15 matrices. Executive function is measured using a shifting attention task; participants match stimuli at the top of the screen with appropriate stimuli choices at the bottom of the screen based on a set of matching rules (i.e., match color or match shape) that change randomly. This task recruits aspects of executive function, including set shifting, updating, and inhibition. Past studies have shown that CNS-VS has comparable reliability to the conventional tests upon which it is based ($r = .65–.85$; Gualtieri, Johnson, & Benedict, 2004).

Clinical Dementia Rating. Global cognitive status was assessed in older adults using the CDR, a semi-structured interview that assesses individuals' cognitive and functional abilities across six domains: memory, orientation, judgment and problem solving, community affairs, home and hobbies, and personal care (Morris, 1993). Scores on each of the domains are combined to obtain a global rating of cognitive impairment ranging from 0 (no impairment) to 3 (severe dementia). A global score of 0.5 is often used as a proxy for mild cognitive impairment.

Statistical Analyses

CNS-VS index scores for verbal memory, visual memory, processing speed, reasoning, and executive function were converted to *z*-scores and averaged to create a global cognition composite score, based on the entire sample of younger and older adults. Prior to analyses, we confirmed that the linear model assumptions were met (i.e., linearity, statistical independence, multivariate normality, and homoscedasticity). Moderation analyses were conducted using hierarchical regression analysis, and continuous variables were mean-centered prior to calculating interaction terms in order to reduce multicollinearity. In Step 1, CFF was entered as the predictor variable; in Step 2, age group (young vs. old) was entered as the moderator variable; and in Step 3, the variable CFF × age group was entered as the interaction term. Global cognition was the first outcome variable and subsequent analyses included verbal memory, visual memory, processing speed, reasoning, and executive function CNS-VS index scores as successive outcome variables. Global ratings on the CDR were used as a covariate in all analyses. Six older adults received a CDR rating of 0.5 and all

Table 1. Descriptive statistics

	Young adults		Older adults	
	Raw scores, *M* (*SD*)	*z*-Scores, *M* (*SD*)	Raw scores, *M* (*SD*)	*z*-Scores, *M* (*SD*)
Critical flicker fusion	25.96 (3.17)	N/A	22.77 (3.04)	N/A
Global cognition	N/A	0.41 (0.41)	N/A	−0.52 (0.58)
Verbal memory	54.5 (3.35)	0.34 (0.69)	50.8 (5.67)	−0.43 (1.16)
Visual memory	40.7 (7.10)	−0.08 (1.07)	41.9 (5.93)	0.11 (0.89)
Processing speed	67.9 (9.73)	0.73 (0.59)	41.1 (9.03)	−0.92 (0.55)
Reasoning	8.87 (3.64)	0.59 (0.72)	2.12 (3.97)	−0.75 (0.78)
Executive function	52.0 (12.7)	0.49 (0.63)	29.9 (20.7)	−0.61 (1.03)

Note: N/A = not applicable.
Raw and standardized scores are presented for all variables with the exception of global cognition (which represents an average of all other standardized cognitive scores) and critical flicker fusion (which is presented in hertz).

Table 2. Correlations between CDR, age group, CFF, and cognition

Variable	1.	2.	3.	4.	5.	6.	7.	8.
1. CDR	—							
2. Age group	−.248**	—						
3. CFF	−230**	−.457**	—					
4. Global cognition	−.474**	−.687**	.377**	—				
5. Verbal memory	−.313**	−.386**	.186*	.670**	—			
6. Visual memory	−.036	.098	−.106	.370**	.107	—		
7. Processing speed	−.359**	−.819**	.344*	.811**	.449**	.039	—	
8. Reasoning	−.404**	−.667**	.386*	.733**	.268**	.058	.600**	—
9. Executive function	−.493**	−.552*	.465*	.800**	.444**	.048	.657**	.556**

Note: CDR = Clinical Dementia Rating scale; CFF = critical flicker fusion. *$p < .05$. **$p < .01$.

younger adults were coded as having a CDR rating equal to 0. Descriptive statistics on task performance can be found in Table 1. Zero-order correlations can be found in Table 2.

Results

Effect of Age Group

As expected, results indicated a significant main effect of age group for global cognition, $\Delta R^2 = 0.346$, $\beta = -0.585$, $t = -8.74$, $p < .001$; verbal memory, $\Delta R^2 = 0.102$, $\beta = -0.336$, $t = -3.658$, $p < .001$; processing speed, $\Delta R^2 = 0.567$, $\beta = -0.797$, $t = -14.213$, $p < .001$; reasoning, $\Delta R^2 = 0.342$, $\beta = -0.571$, $t = -7.929$, $p < .001$; and executive function, $\Delta R^2 = 0.197$, $\beta = -0.357$, $t = -4.823$, $p < .001$. Results for visual memory were nonsignificant.

Effect of CFF

Results indicated a significant main effect of CFF for executive function, $\Delta R^2 = 0.037$, $\beta = 0.496$, $t = 1.998$, $p = .048$. Results for global cognition, verbal memory, visual memory, processing speed, and reasoning were nonsignificant.

Age Group × CFF Interaction

Contrary to hypotheses, analyses revealed no significant interactions between CFF and age group. However, a post hoc hierarchical regression analysis indicated that CFF explained a significant amount of variance in executive function above and beyond age and CDR rating, $\Delta R^2 = 0.037$, $\Delta F(1, 125) = 8.747$, $p = .004$.

Discussion

The processing of CFF involves retinal and cortical processes, but the threshold appears to be determined postreceptorally, at the level of the visual cortex (e.g., Wells, Bernstein, Scott, Bennett, & Mendelson, 2001). The central basis for flicker prompts the question of whether other CNS activities also correlate with CFF thresholds. To test this, we measured CFF and cognition in a sample of younger and older adults. As expected, the younger subjects had both higher average CFF thresholds and performed better on all cognitive measures (with the exception of visual memory that was low and nonvariable for both young and old).

We also hypothesized that individuals with high CFF performance would score better on all cognitive measures than those with low CFF performance. This hypothesis was confirmed only for executive function. Although we predicted that age group would moderate the relationship between cognition and CFF, this hypothesis was not supported. Instead, CFF was a significant predictor of executive function across age groups, and post hoc hierarchical regression analysis indicated that CFF accounts for significant unique variance in executive function performance beyond age group and global cognitive status, as measured by the CDR.

Overall, CFF performance was not a predictor of global cognition or many cognitive subdomains; however, it was uniquely predictive of executive function across both age groups in our sample. This finding is consistent with previous literature which shows that sensory functions and processing speed are important for executive functions (e.g., Albinet et al., 2012; Cronin-Golomb et al., 1995). Additionally, past research on individuals with frontal lobe lesions or tumors indicates that these injuries negatively affect CFF performance (Curran & Wattis, 1998). Traditionally, it has been thought that higher executive

function is regulated primarily by the prefrontal cortex. Perhaps a more realistic view, however, is that executive function involves numerous regions with extensive interaction across brain areas (Alvarez and Emory, 2006). Based on that view, a fast and efficient brain would also have improved executive function. Our results are consistent with that possibility.

One limitation of this study is that average CFF performance for both younger and older adults was slightly higher than previously found in other studies using similar conditions (Renzi & Hammond, 2010). Our overall group mean for CFF was 24.5 Hz, whereas previous overall group means were ~21.2 Hz. This discrepancy could reflect the generally excellent health and high education levels of our sample; younger adults were typically pursuing some level of postsecondary education and older adults had an average of 16.5 years of education. Consequently, our results could have been limited by the high intellectual and educational attainment of the sample. Nevertheless, our study was one of the few that has attempted to measure the relationship between CFF (measured without the common confounds) and cognitive performance, broadly defined. Because CFF thresholds are fast to obtain and inexpensive to measure, they may serve as a good biomarker of higher cognitive function, especially in clinical situations (much as they already do for pharmaceutical research and specific CNS conditions such as encephalopathy; Sharma, Sharma, Puri, & Sarin, 2007). Further study on a more heterogeneous sample is necessary before the specific relation between CFF and brain function can be more completely defined.

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Conflict of Interest

During a portion of data collection and manuscript preparation time, author LMR was employed by Abbott Nutrition.

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