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Discussion

No consistent correlation between baseline pupil diameter and cognitive abilities after controlling for confounds—A comment on Tsukahara and Engle (2021)

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There has been a recent surge of studies examining whether variation in baseline pupil diameter is related to various cognitive abilities such as working memory capacity (WMC), fluid intelligence (Gf), and attention control (AC) to name a few (e.g., Aminihajibashi, Hagen, Foldal, Laeng, & Espeseth, 2019; Bornemann et al., 2010; Heitz, Schrock, Payne, & Engle, 2008; Ralph, Gibson, & Gondoli, 2020; Robison & Brewer, 2020, 2021, in press; Sibley, Foroughi, Brown, & Coyne, 2018; Tsukahara, Harrison, & Engle, 2016; Tsukahara & Engle, 2021; Unsworth & Robison, 2015, 2017a; Unsworth, Miller, & Robison, 2021; Unsworth, Robison, & Miller, 2019; van der Meer et al., 2010). These studies are based, in part, on the idea that baseline pupil diameter is related to functioning of the locus coeruleus-norepinephrine system, which is thought to be important for regulating arousal and alertness (Aston-Jones & Cohen, 2005; Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Joshi, Li, Kalwani, & Gold, 2016; Szabadi, 2013; Unsworth & Robison, 2017b). Despite a number of studies examining potential relations, it is still unclear whether baseline pupil diameter is related to cognitive abilities. That is, many prior studies find near zero correlations between baseline pupil diameter and cognitive abilities (e.g., Aminihajibashi et al., 2019; Ralph et al., 2020; Robison & Brewer, 2020, 2021, in press; Sibley et al., 2018; Unsworth & Robison, 2015, 2017a; Unsworth et al., 2019; see Unsworth et al., 2021 for a meta-analysis of the relation between WMC and baseline pupil diameter), whereas some studies do find a relation (e.g., Bornemann et al., 2010; Heitz et al., 2008; Tsukahara et al., 2016; Tsukahara & Engle, 2021; van der Meer et al., 2010). In a recent attempt to examine discrepancies across studies, Tsukahara and Engle (2021) suggested that differences in luminance (both overall room lighting and screen brightness) influence the correlations between baseline pupil diameter and cognitive abilities such that the correlations seem to arise under dark conditions allowing for more variability between participants. Thus, Tsukahara and Engle (2021) concluded that baseline pupil diameter is related to cognitive abilities under proper lighting conditions.

While the Tsukahara and Engle (2021) results are interesting and important in terms of providing information on how luminance can potentially impact correlations with pupil diameter, it is not clear how robust these results are and whether confounding variables account for the relations. In particular, in a prior study Tsukahara et al. (2016) noted that it was important to account for possible confounding variables such as age and race/ethnicity when examining correlations between baseline pupil dimeter and cognitive abilities. Tsukahara et al. found that there were race/ethnicity and age differences in baseline pupil diameter. Importantly, Gf still correlated with baseline pupil diameter after controlling for these confounding variables (along with others such as nicotine use, medication use, and whether the participant was a college student). Tsukahara et al. (2016) concluded that these analyses provided strong evidence suggesting that the relation between Gf and baseline pupil diameter (note that they did not report the corresponding analyses for WMC) was not due to confounding variables.

In their recent study, Tsukahara and Engle (2021) examined whether age differences could explain their results. In their first study, although age was correlated with baseline pupil diameter and cognitive abilities, each cognitive ability (WMC, Gf, and AC) was related to baseline pupil diameter even after accounting for age. In their second study, using

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structural equation modeling, they found that age accounted for the relation between WMC and baseline pupil diameter, but age did not fully account for the Gf and AC relations with baseline pupil diameter. Unfortunately, Tsukahara and Engle (2021) did not report analyses accounting for both age and race/ethnicity. Thus, it is currently unclear whether the results of Tsukahara and Engle (2021) are robust and will remain once important confounds are controlled for. As such, the goal of the present paper was to reanalyze Tsukahara and Engle's data to examine if there are relations between baseline pupil diameter and cognitive abilities after controlling for confounding variables (age and race/ethnicity) as suggested by Tsukahara et al. (2016). We thank the authors for making their data publicly available.

1. Reanalysis of Study 1 of Tsukahara and Engle (2021)

In their Study 1, Tsukahara and Engle (2021) conducted linear regressions in which each cognitive ability (WMC, Gf, and AC) was entered along with age as predictors of baseline pupil diameter in their gray background condition. We redid these analyses but now also included dummy coded variables for race/ethnicity (Caucasian, Asian, African-American, and Other) based on their coding scheme. Specifically, we specified a hierarchical linear regression in which age and the dummy coded variables for Asian, African-American, and other (Caucasian was the reference variable) were entered in the first step and cognitive ability (WMC, Gf, or AC) was entered in the second step. Note the use of additional dummy coded variables to allow for a finer breakdown of race/ethnicity led to similar results. The results for the three regression analyses are shown in Table 1. Consistent with prior research, age (e.g., Birren, Casperson, & Botwinick, 1950; Tsukahara et al., 2016; Unsworth et al., 2021; Winn, Whitaker, Elliott, & Phillips, 1994) and race/ethnicity (Tsukahara et al., 2016) were both related to baseline pupil size. Critically, only AC still accounted for unique variance in baseline pupil diameter after controlling for both age and race/ethnicity. WMC and Gf did not significantly predict baseline pupil diameter after controlling for confounding variables[1].

Shown in Table 2 are descriptive statistics and correlations between cognitive abilities and baseline pupil diameter as a function of race/ethnicity. As can be seen, there were large race/ethnicity differences in baseline pupil diameter, WMC, Gf, AC, and age (all *p*'s < 0.001, all partial $\eta^2 > 0.05$). Tsukahara et al. (2016) found largely similar and significant correlations between baseline pupil diameter and Gf within each race/ethnicity group, suggesting no moderation effect. However, as shown in Table 2, this was not the case for Tsukahara and Engle (2021), with many of the cognitive ability-baseline pupil diameter correlations failing to reach significance within each group (although this is partially due to lower power). Collectively, these reanalyses suggest that the relations between WMC and Gf with baseline pupil diameter in Tsukahara and Engle (2021) were due to confounding variables. Only AC still predicted baseline pupil diameter when controlling for age and race/ethnicity.

Table 1
Separate hierarchical regression model results predicting baseline pupil diameter for working memory capacity, fluid intelligence, and attention control in Study 1.

Variable	WMC	Gf	AC
Cognitive Ability	0.09	0.11	0.15*
Age	−0.23*	−0.21*	−0.22*
Asian	0.02	0.03	0.04
African-American	−0.21*	−0.18*	−0.19*
Other	−0.03	−0.02	−0.03
R^2	0.14	0.15	0.16
Change in R^2	0.006	0.007	0.02*

Note. Values are standardized betas. WMC = working memory capacity; Gf = fluid intelligence, AC = attention control; * = $p < .05$.

Table 2
Descriptive statistics and correlations as a function of race/ethnicity in Study 1.

Variable	Caucasian ($N = 85$)	Asian ($N = 85$)	African American ($N = 97$)	Other ($N = 48$)
Pupil	5.17 (0.81)	5.20 (0.75)	4.66 (0.80)	5.00 (0.76)
WMC	0.13 (0.73)	0.36 (0.79)	−0.43 (0.77)	−0.05 (0.83)
Gf	0.35 (0.67)	0.47 (0.63)	−0.65 (0.70)	−0.14 (0.81)
AC	0.25 (0.65)	0.14 (0.72)	−0.35 (0.83)	−0.01 (0.74)
Age	21.13 (3.95)	21.93 (3.33)	23.42 (4.38)	23.63 (4.81)
Student	97.6%	100%	85.6%	66.7%
GTech	60.0%	48.2%	8.2%	27.1%
GSU	8.2%	38.8%	22.7%	14.6%
WMC-Pupil	0.26*	0.04	−0.09	0.46*
Gf-Pupil	0.17	0.12	0.15	0.21
AC-Pupil	0.23*	0.07	0.17	0.29*

Note. WMC = working memory capacity; Gf = fluid intelligence, AC = attention control; Student = percentage of students; GTech = percentage of students at Georgia Institute of Technology; GSU = percentage of students at Georgia State University; WMC-Pupil = correlation between working memory capacity and baseline pupil; Gf-Pupil = correlation between fluid intelligence and baseline pupil; AC-Pupil = correlation between attention control and baseline pupil; * = $p < .05$.

2. Reanalysis of Study 2 of Tsukahara and Engle (2021)

We conducted similar reanalyses for their Study 2. Specifically, we did the same hierarchical linear regressions as Study 1. The only difference for Study 2 was that Tsukahara and Engle had baseline pupil measures from eight different lighting conditions. In their correlation analyses they excluded the two brightest conditions. Similar to their analyses, we formed a baseline pupil composite from the remaining six baseline pupil measures. The results for the three separate regression analyses are shown in Table 3. Similar to Study 1, WMC and Gf no longer predicted baseline pupil diameter after controlling for age and race/ethnicity. Additionally, inconsistent with Study 1, AC also no longer predicted baseline pupil dimeter.

To examine whether age accounted for the relations, Tsukahara and Engle (2021) specified three separate structural equation models in which cognitive ability (WMC, Gf, or AC) and age predicted baseline pupil dimeter. They found that Gf and AC (but not WMC) predicted baseline pupil diameter after controlling for age. We reanalyzed their models but now also included dummy coded variables for race/ethnicity. The model for WMC demonstrated acceptable fit, $\chi^2(51) = 80.32$, $p = .005$, RMSEA = 0.05, NNFI = 0.98, CFI = 0.99, SRMR = 0.05. As seen in Fig. 1a, WMC no longer predicted baseline pupil diameter

Table 3
Separate hierarchical regression model results predicting baseline pupil diameter for working memory capacity, fluid intelligence, and attention control in Study 2.

Variable	WMC	Gf	AC
Cognitive Ability	−0.07	0.01	0.04
Age	−0.35*	−0.33*	−0.33*
Asian	−0.23*	−0.23*	−0.22*
African American	−0.33*	−0.31*	−0.30*
Other	−0.13	−0.12	−0.11
R^2	0.20	0.20	0.21
Change in R^2	0.004	0.000	0.001

Note. Values are standardized betas. WMC = working memory capacity; Gf = fluid intelligence, AC = attention control; * = $p < .05$.

[1] Including other demographic variables such as current college student, nicotine use, caffeine use, and sleep resulted in similar overall results.

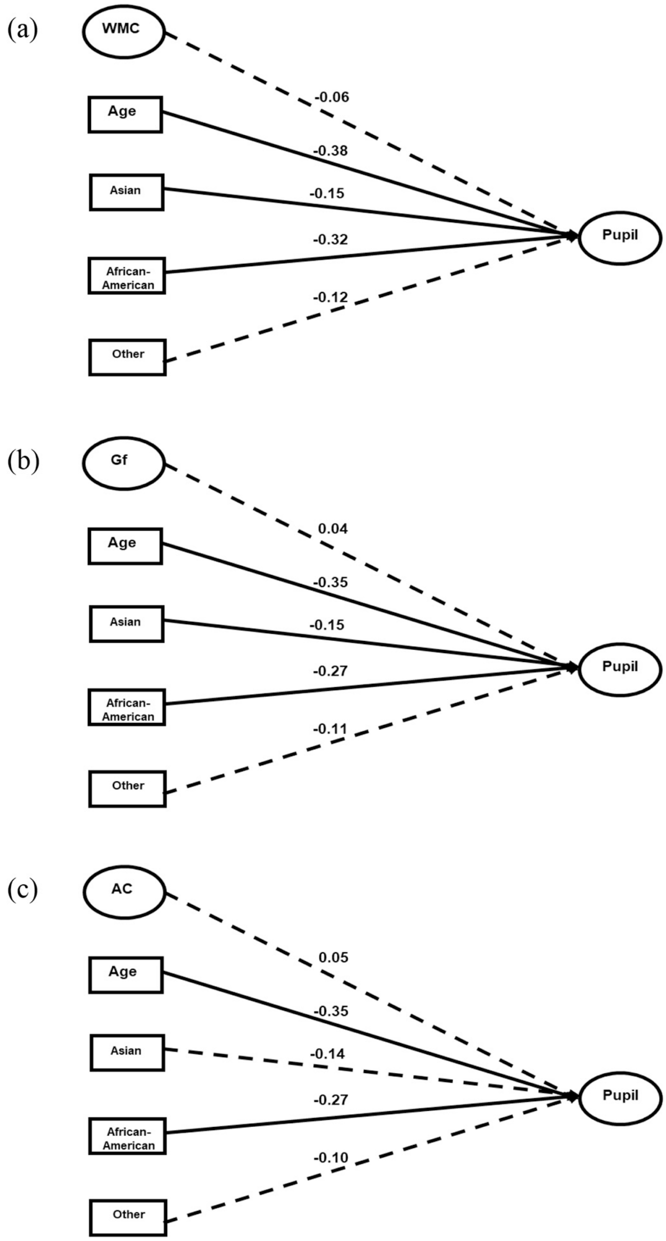

Fig. 1. (a) Structural equation model in which working memory capacity, age, and race/ethnicity predict baseline pupil diameter. (b) Structural equation model in which fluid intelligence, age, and race/ethnicity predict baseline pupil diameter. (c) Structural equation model in which attention control, age, and race/ethnicity predict baseline pupil diameter. Solid paths are significant at the $p < .05$ level, whereas dashed paths are not significant.

after controlling for age and race/ethnicity. Note, for simplicity, correlations among the exogenous factors are not shown. Similarly, the model for Gf demonstrated acceptable fit, $\chi^2(51) = 102.55$, $p < .001$, RMSEA = 0.07, NNFI = 0.96, CFI = 0.97, SRMR = 0.04, and as seen in Fig. 1b, Gf no longer predicted baseline pupil diameter after controlling for age and race/ethnicity. Finally, the model for AC demonstrated acceptable fit, $\chi^2(51) = 83.60$, $p = .003$, RMSEA = 0.06, NNFI = 0.98, CFI = 0.98, SRMR = 0.05, and as seen in Fig. 1c, AC no longer predicted baseline pupil diameter after controlling for age and race/ethnicity. Thus, similar to the regression models, the structural equation models suggested that none of the cognitive abilities predicted baseline pupil diameter after controlling for confounding variables.

Tsukahara and Engle (2021) also examined whether the common variance shared by WMC, Gf, and AC predicted baseline pupil diameter. The authors specified a bi-factor model in which all of the WMC, Gf, and AC tasks loaded onto a common factor, the WMC tasks also loaded on a residual WMC factor, the Gf tasks also loaded on a residual Gf factor, and the AC tasks also loaded on a residual AC factor. Tsukahara and Engle found that the common factor predicted baseline pupil size ($\beta = 0.28$, $p = .004$) and this path remained significant even when accounting for age ($\beta = 0.21$, $p = .01$). Note, that one problem with their model was that none of the Gf or AC tasks loaded significantly onto their residual factors, making it difficult to interpret results from these factors. Nevertheless, we reanalyzed their model but now also included dummy coded variables for race/ethnicity. The model demonstrated acceptable fit, $\chi 2$ (114) = 138.40, $p = .06$, RMSEA = 0.03, NNFI = 0.98, CFI = 0.99, SRMR = 0.04. However, the common factor no longer predicted baseline pupil diameter after controlling for age and race/ethnicity ($\beta = 0.11$, $p = .42$).

Shown in Table 4 are descriptive statistics and correlations between cognitive abilities and baseline pupil diameter as a function of race/ethnicity for Study 2. Similar to Study 1, there were large race/ethnicity differences in baseline pupil diameter, WMC, Gf, and AC (all p's < 0.001, all partial $\eta^2 > 0.09$; differences in age were not significant, $p = .057$). Similar to Study 1, most of the cognitive ability-baseline pupil diameter correlations failed to reach significance within each group. Collectively, these reanalyses suggest that the relations between cognitive abilities and baseline pupil diameter in Study 2 of Tsukahara and Engle (2021) were due to confounding variables.

3. Discussion

In two studies, Tsukahara and Engle (2021) recently found that cognitive abilities (WMC, Gf, and AC) predicted variation in baseline pupil diameter. Tsukahara and Engle (2021) concluded that baseline pupil diameter is related to cognitive abilities under proper luminance conditions. Although Tsukahara and Engle (2021) examined whether the relations were due to age as a confound, they did not examine other possible confounds such as race/ethnicity. This is problematic because prior research by these authors suggests it is important to do so (Tsukahara et al., 2016). Reanalyses of their data accounting for both age and race/ethnicity suggest that only one (AC in Study 1) of the six correlations examined was still statistically significant. These analyses strongly suggest that correlations found in Tsukahara and Engle (2021) were largely due to confounding variables whereby both age and race/ethnicity were related to both cognitive abilities and baseline pupil diameter. Prior research suggests there are moderate relations between

Table 4
Descriptive statistics and correlations as a function of race/ethnicity in Study 2.

Variable	Caucasian	Asian	African American	Other
	(N = 73)	(N = 55)	(N = 38)	(N = 35)
Pupil	5.38 (0.66)	5.07 (0.69)	4.71 (0.81)	5.22 (0.66)
WMC	0.07 (0.75)	0.27 (0.70)	−0.62 (0.78)	0.03 (0.85)
Gf	0.30 (0.64)	0.19 (0.70)	−0.83 (0.90)	−0.05 (0.82)
AC	0.36 (0.55)	−0.03 (0.73)	−0.67 (0.84)	−0.07 (0.81)
Age	23.26 (4.79)	21.95 (3.67)	23.84 (4.81)	21.62 (3.66)
Student	64.4%	89.1%	55.3%	68.6%
GTech	39.7%	34.5%	2.6%	40.0%
GSU	15.1%	47.3%	39.5%	14.3%
WMC-Pupil	0.05	−0.05	0.03	0.13
Gf-Pupil	0.22	0.15	0.02	0.03
AC-Pupil	−0.05	0.29*	−0.01	0.16

Note. WMC = working memory capacity; Gf = fluid intelligence, AC = attention control; Student = percentage of students; GTech = percentage of students at Georgia Institute of Technology; GSU = percentage of students at Georgia State University; WMC-Pupil = correlation between working memory capacity and baseline pupil; Gf-Pupil = correlation between fluid intelligence and baseline pupil; AC-Pupil = correlation between attention control and baseline pupil; * = $p < .05$.

baseline pupil diameter and age even in restricted age samples (e.g., Birren et al., 1950; Tsukahara et al., 2016; Unsworth et al., 2021; Winn et al., 1994). Given that age is also typically related to cognitive abilities, it is critically important to examine whether any relations between cognitive abilities and baseline pupil diameter is due to age.

Similarly, prior research has suggested that there are race/ethnicity differences in baseline pupil diameter (Tsukahara et al., 2016). These differences could be partially due to differences in the size of the iris given that prior research has found race/ethnicity differences in iris size (Lee et al., 2013; Wang et al., 2012), and iris size and baseline pupil diameter are strongly negatively correlated (Wang et al., 2012; Zheng et al., 2016). Thus, the current race/ethnicity differences are likely due to structural differences in the eye, rather than differences in locus coeruleus-norepinephrine system functioning. Furthermore, race/ethnicity differences in cognitive abilities in the current dataset seem likely due to sampling differences. That is, as shown in Tables 2 and 4, many of the Caucasian and Asian participants were students at the Georgia Institute of Technology (GTech), whereas very few of the African-American participants were students at GTech. In fact, only one African-American participant in Study 2 was a student at GTech. This is problematic given that GTech is a highly selective school with an admission rate of roughly 23% (average incoming freshman GPA = 4.0, average SAT scores ranging from 1400 to 1520; information obtained from the GTech admission website). Thus, participants from GTech are more likely to have high cognitive abilities compared to participants from other schools or community volunteers. As such, the race/ethnicity differences in the current dataset likely reflect a sampling artifact whereby certain races/ethnicities are more likely to be sampled from a pool of high ability participants than other races/ethnicities. As noted by Tsukahara et al. (2016), it is critically important to examine whether any relations between cognitive abilities and baseline pupil diameter are due to race/ethnicity differences.

Collectively, reanalyses of Tsukahara and Engle (2021) suggest no consistent correlations between cognitive abilities and baseline pupil diameter after controlling for confounding variables. The current results help clarify discrepant findings in prior studies by demonstrating that when relations between cognitive abilities and baseline pupil diameter are found, these relations are largely due to confounding variables such as age and race/ethnicity.

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