Age Differences in the Subcomponents of Executive Functioning

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Abstract

Objectives: Across the lifespan, deficits in executive functioning (EF) are associated with poor behavioral control and failure to achieve goals. Though EF is often discussed as one broad construct, a prominent model of EF suggests that it is composed of three subdomains: inhibition, set shifting, and updating. These subdomains are seen in both young (YA) and older adults (OA), with performance deficits across subdomains in OA. Therefore, our goal was to investigate whether subdomains of EF might be differentially impacted by age, and how these differences may relate to broader global age differences in EF.

Methods: To assess these age differences, we conducted a meta-analysis at multiple levels, including task level, subdomain level, and of global EF. Based on previous work, we hypothesized that there would be overall differences in EF in OA.

Results: Using 1,268 effect sizes from 401 articles, we found overall differences in EF with age. Results suggested that differences in performance are not uniform, such that variability in age effects emerged at the task level, and updating was not as affected by age as other subdomains.

Discussion: These findings advance our understanding of age differences in EF, and stand to inform early detection of EF decline.

Keywords: Aging; Executive Function; Unity-Diversity Model; Meta-Analysis

Age Differences in the Subcomponents of Executive Functioning

Executive functioning (EF) is one's ability to successfully select and manipulate information and use that information appropriately to achieve a goal. In advanced age, individuals experience cognitive deficits in multiple domains (Grady, 2012; Hedden & Gabrieli, 2004), including EF (Bopp & Verhaeghen, 2005; Braver & Barch, 2002; Verhaeghen & Cerella, 2002). EF declines in older adults (OA) can make even simple daily tasks difficult (Vaughan & Giovanello, 2010), reducing independence and increasing burden on others. However, while it is well known that increased age is related to poorer performance on cognitive tasks, little research has sought to quantify age-related differences across subdomains of EF between younger (YA) and OA within an existing model of EF. This quantification is critical for a better understanding of differences in EF performance across the lifespan. Furthermore, most meta-analyses conducted to date have focused on specific subdomains of EF (Bopp & Verhaeghen, 2005; Rey-Mermet & Gade, 2018; Rhodes, 2004; Salthouse, 1996; 2009; Verhaeghen, 2011; Verhaeghen & Cerella, 2002; Verhaeghen, Steitz, Sliwinski, & Cerella, 2003; Wasylyshyn, Verhaeghen, & Sliwinski, 2011). To understand how EF declines in aging it is critical to make comparisons across subdomains. Doing so may inform future work aimed at developing more precise remediation techniques to improve lost ability in advanced age.

EF is a broad and diverse construct; this is made evident in the number of theoretical conceptualizations used to describe it (Hale & Fiorello, 2004). This is seen clearly in a targeted review which found that for the 60 most highly cited articles on EF from 1970 to 2007, 98 different tasks were used to assess EF (Packwood, Hodgetts, Tremblay, 2011). Further, 68 terms were used to describe subcomponents of EF, including broad characterizations such as inhibition, working memory, fluency, sequencing, set shifting, etc. Additionally, many of the 98 tasks used to assess EF were used across several of the 68 terms used to describe EF, suggesting that one task might contribute to multiple aspects of EF. The results of latent modelling analyses found 18 unique terms for EF (Packwood et al., 2011). This diversity is also seen in the number of models developed to organize and describe EF, with some models describing EF through a global construct such as working memory (Baddeley, 1992) or attention (Norman & Shallice, 1986). Other models consider EF as a broad construct made up of several subdomains such as information updating and monitoring, mental set shifting, and inhibition of prepotent responses (Miyake et al., 2000; Miyake & Friedman, 2012; Friedman & Miyake, 2017). Finally, other models use a neuroanatomical approach in which brain regions are related to different functions critical to successful EF (Miller & Cohen, 2001; Banich, 2009). While many EF models express similar constructs in an attempt to explain EF, their differences prompt the use of distinct tasks and procedures to draw conclusions (Packwood et al., 2011). Given this heterogeneity in the models, subdomains, and tasks used to describe EF, it is beneficial to assess EF using a wide range of tasks in an attempt to understand how EF might differ in advanced age.

Though the literature examining EF is broad and a wide variety of tasks are used to assess the many EF subdomains (Hale & Fiorello, 2004; Packwood, Hodgetts, & Tremblay, 2011), several consistent findings emerge when specific subdomains of EF are examined in isolation. Briefly, work examining broad subdomains of EF such as attention (Verhaeghen & Cerella, 2002), dual tasking (Verhaeghen et al., 2003), inhibition (Langenecker, Nielson, & Rao, 2004; Rey-Mermet & Gade, 2018; Rey-Mermet, Gade, & Oberauer, 2018; Spieler, Balota, & Faust, 1996; Verhaeghen, 2011; Verhaeghen & Cerella, 2002; Verhaeghen & De Meersman, 1998a, 1998b; West & Alain, 2000), processing speed (Salthouse, 1996; Salthouse, 2009; Verhaeghen & Salthouse, 1997), set shifting (Ashendorf & McCaffrey, 2008; Fristoe, Salthouse, & Woodard, 1997; Rhodes, 2004), task switching (Verhaeghen, 2011; Verhaeghen & Cerella, 2002; Wasylyshyn et al., 2011), updating (Linden, Bredart, & Bredart, 1994; Zeintl, & Kliegel, 2009), and working memory (Bopp & Verhaeghen, 2005) show a general pattern wherein OA exhibit performance deficits relative to YA. However, some work has found that under optimal conditions these differences can be reduced (Anderson, Campbell, Amer, Grady, & Hasher, 2014; Hsieh & Fang, 2012; Salthouse, Atkinson, & Berish, 2003; Verhaeghen & Cerella, 2002). Critically, there has been limited work to date comprehensively comparing subdomains of EF in the same analysis. That is, little work has looked to determine whether subdomains of EF differ with age to the same degree or if some subdomains see relative sparing. Thus, a quantitative assessment examining the impact of aging on subdomains of EF is warranted, and stands to provide greater insight into how EF performance differs and why global EF might change in OA. Furthermore, the inclusion of processing speed measures in the context of EF subdomains is of great importance. Salthouse (1996, 2009) demonstrated that processing speed is slower in OA, which contributes to age differences in cognition, broadly defined, including EF.

To this end, this investigation had two aims. First, we wanted to examine the overall magnitude of difference in performance on EF tasks in YA and OA. Second, we wanted to understand how the magnitude of difference in individual subdomains of EF relate to the overall age differences in EF. Specifically, we tested whether EF subdomains are uniformly different in OA, or if some subdomains are more or less impacted by advanced age. Related to our second aim, we wanted to understand how processing speed differences relate to EF, and whether or not a unique pattern of difference across multiple domains (inhibition, updating, and shifting, in addition to processing speed) would emerge. To assess these questions, we conducted a meta-analysis across 24 years of behavioral research investigating age differences in EF, using an inclusive model that is suited to assess the heterogeneity seen in the EF literature, as it allows a wide range of tasks to be easily sorted into three broad subdomains of EF.

Material and Methods

Study Selection and Qualitative Coding

As EF is a complex and heterogeneous construct (Packwood et al., 2011), we chose to organize our work using an established and accepted EF model that was developed, in part, to reduce the number of terms required to categorize EF tasks into subdomains and increase the inclusivity of tasks, allowing us to examine a heterogenous EF literature (Packwood et al., 2011). The Unity-Diversity Model of EF is a widely used model of interest, particularly for its use in work assessing EF across the lifespan (Miyake et al., 2000; Miyake & Friedman, 2012, Friedman & Miyake, 2017; Karr et al., 2018). This model broke EF down into three subdomains: information updating and monitoring, mental set shifting, and inhibition of prepotent responses. Critically, these three subdomains work together to form the construct of EF (unity), however, they also function as distinct subdomains (diversity). Breakdowns in one or more of the subdomains can manifest as executive dysfunction. Fisk and Sharp (2004) expanded on this model with a lifespan approach, including individuals between the age of 20 and 81. Critically, the same three factors found by Miyake et al. emerged in both YA and OA, but OA had performance deficits across all three subdomains. Subsequent iterations to the Unity-Diversity Model suggest that inhibition is subsumed by common EF (Miyake & Friedman, 2012; Friedman & Miyake, 2017) while other work suggests inhibition might consist of several distinct inhibitory processes as a correlational relationship could not be found among different inhibition tasks (Kramer, Humphrey, Larish, and Logan, 1994). However, inhibition was used here as a separate subdomain given the robust literature on response inhibition (Diamond, 2013) and its inclusion in subsequent re-analyses of the Unity-Diversity Model (Fisk & Sharp, 2004; Karr et al., 2018) as well as later iterations of the model (Miyake & Friedman, 2012; Friedman & Miyake, 2017). Nonetheless, the Unity-Diversity Model (Miyake & Friedman, 2012; Friedman & Miyake, 2017) provides a broad framework for EF that is applicable across the lifespan (Fisk & Sharp, 2004), and as such served as the organizational and theoretical framework for our meta-analysis.

To this end, we searched Medline (Ovid) on June 25th, 2017 in accordance with the language used in the Unity-Diversity Model of EF (Friedman et al., 2008; Miyake & Friedman, 2012; Friedman & Miyake, 2017). The search terms included the following: executive function, cognitive control, inhibition, updating, and any combination of task/set switching/shifting. Notably, however, we limited the paper inclusions to those that were found in our initial search with the terms described above, using the subdomains described by Miyake and colleagues (Miyake & Friedman, 2012; Friedman & Miyake, 2017). For example, though working memory tasks are included with updating, we did not conduct an additional search on working memory. Critically, our analysis included a large sample of studies across subdomains, in an attempt to address our second aim of understanding age differences in EF at the subdomain level, as meta-analyses comparing YA and OA on some specific tasks have already been conducted (e.g., Bopp & Verhaeghen, 2005; Rey-Mermet et al., 2018; Verhaeghen, 2011; Verhaeghen & Cerella, 2002; Verhaeghen & Salthouse, 1997; Verhaeghen et al., 2003; Wasylyshyn et al., 2011).

In addition to these search terms, articles were limited to those that included: young adults (18-35), older adults (65+), research conducted on human subjects, and articles written in English. These terms and limitations were used in a single search using the search script provided in Supplementary Table 1, and also available for download from the Open Science Framework (https://osf.io/z4vga/).

Once the articles were collected, trained research assistants completed an initial examination of the article. Studies were included if the article: examined both healthy young (18-35) and older (65+) adults, made direct comparisons between the two age groups, and if participants completed at least one behavioral task, though we did not have research assistants reject articles based on task. However, with these criteria, we were able to eliminate reviews, case studies, meta-analyses and articles that did not include both healthy YA and OA. We only looked at studies of healthy controls or those that reported participants as healthy young or older adults. Articles were reviewed to ensure that no clinical populations were included. The resulting articles were then critically examined for inclusion for analysis by authors T.M. and J.R.M.G. For this second, more thorough review, each task in the article was further reviewed to ensure it fell within the parameters of the Unity-Diversity Model (Miyake & Friedman, 2012; Friedman & Miyake, 2017). Additionally, processing speed was assessed as operationally defined by Salthouse (1992, 1996). Task inclusion criteria are provided in a Supplemental Methods, Results and Discussion section. Additionally, Supplementary Table 2 lists and describes each task and the dependent variable used in the analysis.

The final set of articles were dual-coded by authors T.M. and J.R.M.G. for the EF task performed and the subdomain it fell under, based on the subdomain characteristics outlined in the Unity-Diversity Model (Miyake & Friedman, 2012; Friedman & Miyake, 2017). If multiple conditions for a task were reported, the condition that most closely resembled the standard task paradigm was recorded to ensure OA were not inherently placed at a performance disadvantage. For instance, if participants completed a 1-back, 2-back and 3-back task, we chose the 2-back, as the 1-back typically serves as the control condition. Once the tasks were placed in a subdomain and the appropriate conditions were chosen, the most task relevant performance metric was determined (see Supplementary Table 2). These were determined on a task-by-task basis; however, we tried to use the most commonly used metric for the task, such as the Stroop Effect for the Stroop Task. If such a metric was not provided, we used the reaction time or accuracy measure that we believed most accurately represented the task, such as the RT for incongruent trials on a Stroop task. Figure 1 graphically displays the progression of article inclusion/elimination explained above.

[Insert Figure 1 here]

The remaining studies were also coded for mean age, age range, sample size, and metric used (i.e.: RT, accuracy, error rate, Stroop Effect, etc.; see Supplementary Table 2). Additionally, many studies included multiple EF tasks. In these instances, average effect sizes were computed such that each study had one effect size for each subdomain represented in the study.

Quantitative Analyses

All analyses were performed in R v3.3.1 (R Core Team, 2013). Hedges' g, an effect size statistic that corrects for an upward bias seen in Cohen's d, was computed in R by author T.M. for each study using differences in mean performance scores and standard deviations between younger and older adults, and was interpreted similarly to Cohen's d. In cases where means and standard deviations were only presented graphically, WebPlotDigitizer v3.12 (Rohatgi, 2017) was used to estimate these data. Less than .01% of the data were transformed (Supplementary Table 2). Positive effect sizes indicated better performance for YA and negative effect sizes indicated better performance for OA. Three levels of analyses were used. First, age differences in task performance were computed for any task with 10 or more effect sizes. Then, tasks were grouped by task subdomain (Miyake & Friedman, 2012; Friedman & Miyake, 2017) to understand age differences at the subdomain level. Lastly, all effects sizes were assessed to understand global age differences in EF.

The Metafor (Viechtbauer, 2010) and MAd (Del Re & Hoyt, 2010) packages in R were used to complete our analyses. For studies with multiple effect sizes, we calculated average effect sizes using MAd (Del Re & Hoyt, 2010), such that each study only had one effect size per subdomain, per study, following procedures outlined by Borenstein, Cooper, Hedges, and Valentine (2009), with minor exceptions explained below. Meta-regressions, which are interpreted as a traditional linear model ANOVA, were used to examine age differences at the task levels. For analyses at the subdomain and global EF level, we ran multivariate analyses to account for the multiple outcomes the averages represent (Cheung, 2019). Moderator analyses were used to understand whether age differences existed between subdomains. The was done by dummy coding each subdomain within the multivariate model. We should note, during these moderator analyses, it was possible that some studies had more than one effect size in the analysis. For instance, if we were interested in differences between subdomains, there was a possibility that each subdomain might have an effect size from the same study if multiple tasks were used. All analyses used random effects models. Chi-square tests were used to assess heterogeneity of effect sizes. A p-value of .05 was used in all analyses, except for the moderator analyses wherein we used a Bonferroni correction.

Results

The search of Medline (Ovid) resulted in 6,714 articles (Figure 1). When duplicates were removed, 6,276 articles remained for further evaluation. Following the first review of the data, 5,348 articles were excluded. The majority of the exclusions resulted from a lack of healthy control groups or there not being a direct comparison between YA and OA. This resulted in 928 articles. Of the 928 critically examined articles, 277 were eliminated for not meeting inclusion criteria and 316 articles required data requests from the authors. After emailing each of the 316 authors, 66 authors were able to provide data and 48 authors indicated that they no longer had access to the data or were unable to fulfill the request because the data did not meet inclusion criteria. The remaining authors did not respond. Accordingly, 401 articles produced 438 independent experimental samples, yielding 1,268 effect sizes for the final analysis (see Supplementary Table 2).

A funnel plot was used to subjectively assess whether publication bias, occurred in our sample of studies (Sterne & Egger, 2001). A symmetric plot suggests there is no bias in publication selection and an asymmetric plot suggests bias. Supplementary Figure 1 shows some asymmetry, suggesting some bias in the publications used in the sample. However, we believe this might be the result of poor study yield from our data requests. Approximately 38% of the potentially eligible articles (250) were not included because the data no longer existed or requests for data were not answered. However, due to the large number of articles included in this analysis, and the minimal asymmetry, we felt confident in drawing conclusions using the current data set, but exercise some caution in our interpretations knowing that the entirety of the literature might not be represented in the present analysis.

Age Differences Across EF Tasks

We first looked to understand age differences in EF at the task level. Eligibility for task level analyses required that a task have at least 10 effects sizes, resulting in 21 eligible tasks and 853 effect sizes. Table 1 provides information on which tasks were included, the effect sizes (*g*), their confidence intervals (*CI*), heterogeneity statistics (I^2, σ^2 *and* Q), and how many effect sizes were in each group (*n*). I^2 was used for meta regressions and describes the percentage of variation across studies. σ^2 was provided for the multivariate analyses and describes the standard deviation of the population. 16 tasks showed a significant age difference ($p<.002$) following a Bonferroni correction, such that OA performed worse on these tasks than YA. While an analysis examining which of these tasks differed from one another would not be statistically viable because of the large number of multiple comparisons, it is considered common practice to use confidence intervals in these situations to begin to understand which tasks might be different (Green & Higgins, 2005). Specifically, if confidence intervals do not overlap, it is suggested that the effects differ from each other. To this end, Figure 2 provides a visualization of effect size differences.

[Insert Table 1 here]

[Insert Figure 2 here]

In general, YA performed better than OA, with effect sizes ranging from 0.31 to 2.12, with most effects ranging between 0.5 and 1.5. Of note, while many commonly used paradigms such as the Stroop (g=2.11), n-back (g=0.83), and Wisconsin Card Sorting tasks (g=0.93) all showed significant age differences, other commonly used tasks, such as the Go/No-go (g=1.16) did not show significant age differences. Interestingly, the magnitude of age differences was not uniform across the tasks.

Age Differences in EF Subdomains Defined by the Unity-Diversity Model

We next wanted to understand whether age differences would emerge within subdomains of EF, and if the subdomains would be equally affected by age. As described above, the Unity-Diversity Model (Miyake & Friedman, 2012; Friedman & Miyake, 2017) was used to place tasks within subdomains (inhibition, shifting, and updating). As a result of using these inclusion criteria, we were able to add more effect sizes for tasks that were not included in our task-level analysis. We added 415 more effect sizes to the analysis, for a total of 1,268 effect sizes.

We first examined age differences on the subdomains of EF outlined by the Unity Diversity Model (Miyake & Friedman, 2012; Friedman & Miyake, 2017; See Table 2). The analysis of age effects on inhibition yielded a significant effect size, $g = 1.64$ (*CI*: 1.33, 1.95), $p<0.001$, and had significant heterogeneity $\sigma^2 = 4.06$, $Q\ (227) = 1{,}312.56$, $p<0.001$. Additionally, age effects for updating ($g=0.80$; *CI*: 0.68, 0.92), shifting ($g=1.40$; *CI*: 1.02, 1.79) and processing speed ($g=1.50$; *CI*: 1.19, 1.80) were also significant ($ps>0.001$), with similarly significant heterogeneity statistics ($ps>0.001$; Table 2). The results of these subdomain analyses are presented in Table 2 and presented visually in Figure 3. Due to the number of effect sizes used in the analysis, the density of the forest plots made interpretation of the information difficult (Supplementary Figures 2-8), therefore a summary plot (Figure 3) is provided to more clearly depict the results. Figure 3 depicts the summary effect sizes from each subdomain analysis, and these summary plots are included for all subsequent analyses. In brief, EF performance in inhibition, updating, shifting and processing speed ($ps<0.001$; Supplementary Figures 3-6, respectively) was significantly worse in OA relative to YA.

[Insert Table 2 here]

[Insert Figure 3 here]

To understand whether the effect sizes of the subdomains of EF differ, suggesting differential age effects on some EF subdomains, we conducted follow-up analysis between the subdomains. After a multiple comparisons correction, we found that updating was significantly different from inhibition ($p=0.001$), shifting ($p=0.001$), and processing speed ($p=0.001$), such that updating did not see as large of an age effect as the other subdomains. No other effects reached significance (p>0.064). These findings further validate the unity/diversity aspect of this model such that the differences seen in subdomains are similar to those differences found in overall EF (unity), but also show some differences between subdomains (diversity).

Lastly, we examined age differences in overall EF, by collapsing across all EF subdomains (Supplementary Figure 2), to show broad differences in EF. The analysis of age effects on EF yielded a significant effect size, g= 1.29 (*CI*: 1.12, 1.47), p<0.001, and test for heterogeneity was significant $\sigma^2 = 2.23$, Q (437) = 1,629.01, p<0.001.

Exploratory Analyses

Several sets of exploratory analyses are discussed in the Supplemental Methods, Results and Discussion section. These include further analyses for the updating and processing speed subdomains and an assessment of whether tasks used by Miyake et al. (2000) to describe EF show similar age-effects to other tasks tapping into similar processes, but not included in the initial investigations by Miyake and colleagues (Miyake et al., 2000; Miyake & Friedman, 2012; Friedman & Miyake, 2017**)**. Chiefly, we found that the sparing exhibited in the updating task subdomain might be the result of maintained verbal ability in older adults.

Discussion

The current literature consistently demonstrates differences in EF in OA relative to YA (Ashendorf & McCaffrey, 2008; Spieler et al., 1996; Zeintl & Kliegel, 2009), but the magnitude of differences between EF subdomains has not been comprehensively explored and compared in one analysis. Understanding the magnitude of age differences in EF is important for the development of targeted interventions to improve EF performance in advanced age and improve early detection of EF deficits in OA. The goal of the present study was to understand the degree of difference in EF between YA and OA, on the global, subdomain, and task levels.

EF Task Performance

We first examined age differences in EF task performance across 21 different tasks (see Table 1 for a full list). Though there have been meta-analyses of specific EF subdomains (Bopp & Verhaeghen, 2005; Rey-Mermet & Gade, 2018; Wasylyshyn et al., 2011), age differences on many EF tasks have not been explored across studies. Unsurprisingly, many of the tasks known to experience age-related decline, such as Stroop, Flanker, Trails Making Task, WCST, Digit Span, and n-back, showed significant differences in performance, such that OA performed worse than YA. This is consistent with previous meta analytic work that showed declines in attention (Verhaeghen & Cerella, 2002), dual tasking (Verhaeghen et al., 2003), inhibition (Rey-Mermet & Gade, 2018; Rey-Mermet et al., 2018; Verhaeghen, 2011; Verhaeghen & Cerella, 2002; Verhaeghen & De Meersman, 1998a, 1998b), task switching (Rhodes, 2004; Verhaeghen, 2011; Verhaeghen & Cerella, 2002; Wasylyshyn et al., 2011), and working memory (Bopp & Verhaeghen, 2005). We have extended these important findings to include data about age differences across many more task types, providing an additional level of detail and nuance to our understanding of age differences in EF.

Here, we found age differences in the Stroop Task. However, some previous work found no age differences in the Stroop Effect (Verhaeghen & De Meersman, 1998b; Langenecker et al., 2004). Verhaeghen & De Meersman (1998b) suggested that age differences in the Stroop Effect can be accounted for by general slowing. Critically, we found that YA perform 2 standard deviations better than OA (g=2.11). In all likelihood, past work suggesting no age differences in the Stroop Effect might be the result of differences in the number of effect sizes included here (n=103), relative to Verhaeghen & De Meersman's (1998b) work (n=20) and the different ranges of sampled response latencies. Both matters are noted limitations for the type of analysis

(Perfect, 1994) used in Verhaeghen & De Meersman's (1998b). Critically, our work here provides an updated view of the current literature on the Stroop Effect in aging. Notably however, we did not specifically investigate this slowing hypothesis, and this may be contributing to the age effect found in this analysis.

Although YA generally performed better on most EF tasks, there are some tasks for which the age differences were smaller or there were no age differences. Importantly, subcomponents of EF might reflect task specific behaviors and not EF specific functions (Packwood et al., 2011). That is, models that use specific tasks to describe EF might be representing age differences for task specific performance with little input of the EF process that is affecting that difference. This is evident in the current work, where there were significant age differences on a Trail Making Test B, but not broader Task Switching Tasks. Though both tasks examine task switching, only one shows an age difference in task performance. This might be further evident in the heterogeneity statistics for our subdomain level analyses (See Table 2) which indicate that there are several subsamples within our data. These subsamples may be due to age effects on task-specific performance.

It is also notable that within a given task, age differences are variable (Supplemental Figure 2). In some samples OA performed better than YA, underscoring the heterogeneity of the sample and individual differences in EF performance in OA. Our findings here support the notion that some OA might not be as susceptible to age-related cognitive differences, though conditions under which EF is assessed might also impact the results (e.g., Anderson et al., 2014). Understanding the underlying factors associated with superior performance in OA, and the boundary conditions to optimize performance in OA may be particularly informative for future work on remediation.

EF Subdomain Performance

We next examined differences within subdomains of EF as defined by a well-accepted EF model (Miyake & Friedman, 2012; Friedman & Miyake, 2017). The EF subdomains showed differences of large magnitude, such that OA performance was over one standard deviation below that of YA on all subdomains, except for updating. Updating is relatively functionally spared, such that the magnitude of difference was not as large as in inhibition, and shifting. We suggest that this is due to the relative stability of vocabulary across the lifespan (Singh-Manoux et al., 2012; Supplemental Methods, Results and Discussion). However, the use of accuracy to assess performance, as compared to reaction time which is used for shifting and inhibition, may be contributing to this smaller age difference. There is a consistent and proportional slowing of reaction times in OA (Cerella, 1994; Cerella & Hale, 1994; Myerson, Hale, Wagstaff, Poon, & Smith, 1990; Verhaeghen & Cerella, 2002). As such, subdomains relying on reaction time measures might show an exaggerated age affect because of this proportional slowing, as compared to the updating subdomain which primarily relies on accuracy measures.

Given that there are large differences across subdomains of EF, future research focusing on EF more holistically might be particularly beneficial. Critically, in the Unity-Diversity Model (Miyake & Friedman, 2012; Friedman & Miyake, 2017) all three subdomains of EF are distinct, but also share variance that contribute to global EF. Therefore, more emphasis might be placed on examining the relationships between EF subdomains (unity) instead of examining each subdomain in isolation (diversity; Snyder, Miyake, & Hankin, 2015). Though typically EF subdomains have been examined in isolation (Bopp & Verhaeghen, 2005; Rey-Mermet & Gade, 2018; Rey-Mermet et al., 2018; Verhaeghen & Salthouse, 1997; Verhaeghen & Cerella, 2002; Verhaeghen et al., 2003; Verhaeghen, 2011; Wasylyshyn et al., 2011), more work might seek to assess multi-domain training programs. Indeed, recent work by Binder et al. (2016) found preliminary support for this idea, such that individuals in a multi-domain training group saw overall greater improvement on cognitive tasks, than participants who received training in a single subdomain. This type of remediation training might be useful in improving executive function more broadly particularly for OA, allowing for quicker and more meaningful improvements.

Processing Speed

Though there is general support for age differences in EF performance, the role of processing speed is also of note. Salthouse (1996, 2009) demonstrated that processing speed is slower in OA, which contributes to age differences in cognition, broadly defined, including EF. Salthouse (1996) suggested that an inability to manage information in a timely manner to reach a goal contributes to EF differences in advanced age. This stands in contrast to other models of EF that suggest differences in various subdomains result in poor EF performance (Miyake et al., 2000; Miyake & Friedman, 2012; Friedman & Miyake, 2017; Fisk and Sharp, 2004). Thus, understanding the role of processing speed with respect to EF and subdomains of EF in OA is of great interest, particularly if this creates a more parsimonious model of age-related differences in EF (Salthouse, 1996).

While processing speed did have the largest age effect, there was variability in the degree of age differences in performance across subdomains of EF. That is, even with large age differences in processing speed, updating is not impacted to the same degree as other domains of EF in OA. This suggests that processing speed may not be the sole driver of age differences in EF. Critically however, we also cannot rule out the idea that these different subdomains are differentially reliant upon processing speed, further contributing to the differing age effects between domains. In line with examining the unity aspects of the model, the incorporation of processing speed into our understanding and investigations of EF in advanced age is certainly warranted and critical. While our results indicate that processing speed may not be the driving force behind age differences, this domain likely still has a great impact on cognition in OA (Cerella, 1994; Verhaeghen & Cerella, 2002).

Overall EF Performance

Lastly, we examined overall age differences in EF. In line with the extant literature, the current data revealed age differences in overall EF performance. The magnitude of difference is of interest. The Hedge's g for overall EF was 1.29, meaning that OA performance was about one standard deviation below YA. This is echoed in an exploratory analysis which looked at tasks used by Miyake (g=1.55) and tasks that fall into the same domain but not used in the original tests of the Unity-Diversity model (g=1.16) separately (please see Supplementary Methods, Results and Discussion). This highlights the large discrepancy in performance between YA and OA. Critically, it also provides a tangible number to evaluate global progress in remediation programs, such that we can better understand overall program efficacy, be more precise when tracking progress, and more accurate when assessing the degree of improvement. On the other hand, it may be similarly important for tracking normative declines and differentiating those from more pathological changes experienced by some OA. Further, particular emphasis might focus on a unified approach, such that remedial techniques are applied across multiple subdomains of EF, and not in isolation, to maximize benefits that might further translate to global EF improvements.

Limitations

Though meta-analyses provide a powerful approach to understanding a broad literature, there are also several limitations. The first limitation is with respect to the scope of our analysis. Our sample included over 400 articles and 1,260 effect sizes, which is excellent for improving our confidence in the current findings; however, we were unable to uncover smaller, more nuanced trends in the data. Many Q, σ^2 and I^2 statistics (Table 2) for subdomains indicated there were more subgroups in the sample, which might be due to a variety of factors including (but not limited to) the tasks used to investigate the subdomain, the broad inclusion criteria used when including tasks into subdomains, overall sample age, socio-economic status, and education level. But, these follow-up analyses are outside the scope of this investigation. As discussed previously, EF can be broken into multiple subdomains with varying inclusion requirements (Friedman et al., 2008; Miyake & Friedman, 2012; Packwood et al., 2011). Though updating, set shifting, and inhibition have been widely researched, these are not the sole subdomains that describe executive function (e.g. dual-task ability; Packwood et al., 2011). With that said, the Unity-Diversity Model (Miyake & Friedman, 2012; Friedman & Miyake, 2017) is quite inclusive with broad parameters for each subdomain, providing a broad framework for our investigation. However, the broad nature of the model does create issues, especially when tasks that fall within the same subdomain might conceptually examine different constructs within that subdomain. For instance, Ecker, Lewandowsky, Oberauer and Chee (2010) demonstrated that updating as a cognitive process can be further divided into retrieval, transformation, and substitution. The authors further argue that these processes are separate from working memory, which is commonly thought of as being involved in updating (Ecker et al., 2010). For instance, in Ecker et al. (2010), an n-back task would be considered updating because it has a retrieval and substitution component, whereas an operation span task would be characterized as a working memory span task. Thus, two tasks that were both placed in the updating subdomain might examine different processes within a subdomain. But, with the parameters defined by Miyake and colleagues (Miyake & Friedman, 2012; Friedman & Miyake, 2017), these nuances were not considered. However, we wanted to adhere to a well-accepted model of EF, and thus focused on those subdomains as they capture many of the tasks regularly used in the cognitive aging literature.

Also, we ran multivariate analyses to account for the multiple outcomes the average effect sizes represent (Cheung, 2019). However, in some instances multiple effect sizes were used from a single study, jeopardizing the assumption of independence. For example, it is possible that a single study had an effect size for both inhibition and updating as more than one task was used, resulting in a single study having multiple effect sizes in the analysis. However, we believe that because these effect sizes represent different constructs, and use different cognitive processes, the issue of independence is lessened (though of course not completely eliminated). We fully acknowledge that this is not ideal, however, we believe it is necessary to complete these analyses. This is in line with meta analyses that use several studies from the same research group as effect sizes can be influenced by common factors, like study design, population characteristics, sampling strategies and research staff. These effect sizes are likely to be non-independent, but are generally not corrected (Van den Noortgate et al., 2013; Cooper, 2009).

Additionally, work has suggested that cross-sectional data tends to exaggerate cognitive decline in early older adulthood, possibly due to generational biases (Nyberg, Lövdén, Riklund, Lindenberger, & Bäckman, 2012). Critically, all of the data used in this investigation was cross-sectional. Since the current work requires concatenation across the data and does not consider age ranges within age groups, we might run the risk of inflating the degree of difference between YA and OA. Thus, the current work might only provide approximation and future work might benefit from longitudinal designs to more accurately estimate change over time. Lastly, we only included articles that directly compared YA and OA. While this decision reduces the number of comparable effect sizes, it also reduces the amount of error by ensuring performance scores for YA and OA performance are obtained under similar experimental conditions.

Conclusions

Age differences in cognitive performance, including in EF, are a well-known phenomenon. However, the magnitude of these differences, across studies, sites, and samples, has not been quantified in one investigation and only gauged within individual subdomains. The current work provides a comprehensive overview of the current literature from the task level through global EF. Further, we demonstrated a large difference in overall EF and a similar degree of difference in subdomains in EF, with the exception of updating. This new understanding in the magnitude of difference further informs remediation in OA, and improves our understanding of age differences in EF performance, within the context and framework of a well-accepted and studied model of EF.

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Table 1.

Meta Statistics by Task.

	g	CI	I^2	Q	n
			Inhibition		
Stroop	2.11**	1.47, 2.76	94.03%	1,693.17*	102
Flanker Task	1.99**	0.97, 3.01	67.74%	68.19*	23
Inhibition Tasks	0.50*	0.07, 0.93	0.00%	11.62	18
Go/No-Go Task	1.16	-0.04, 2.36	77.51%	71.15*	17
Stop-Signal Task	1.77*	0.28, 3.27	31.55%	16.07	12
Hayling Task	0.76**	0.43, 1.10	0.00%	3.63	11
			Updating		
Verbal Fluency	0.50**	0.30, 0.70	59.49%	318.44*	130
Digit Span	0.68**	0.49, 0.87	74.10%	471.01*	123
n-back	0.83**	0.50, 1.16	43.24%	54.62*	32
Updating Task	0.90**	0.63, 1.16	13.15%	24.18	22
Reading Span Task	0.84**	0.64, 1.03	0.00%	12.44	25
Letter Number Sequencing Task	1.51**	1.05, 1.96	64.81%	45.47*	17
Computation Span Task	1.43**	0.90, 1.97	59.58%	22.27*	10
			Shifting		
WCST	0.93**	0.53, 1.32	79.82%	223.01*	46
Trail Making Task B	1.54**	1.03, 2.05	64.56%	174.97*	63
Task Switching Task	2.12	-0.06, 4.30	85.79%	161.91*	24
			Processing Speed		
Digit Symbol Substitution Task	1.65**	1.20, 2.10	83.92%	615.60*	100
Trail Making Test A	2.00**	1.02, 2.98	90.12%	374.47*	38
Processing Speed Task	1.69**	0.75, 2.63	83.02%	94.26*	17
Choice RT	1.66**	0.57, 2.76	0.00%	1.09	12
Letter Comparison Task	0.31	-1.74, 2.35	97.60%	416.65	11

Note. ** *p*<.001 in accordance to a Bonferroni correction; * *p*<.05 uncorrected; g= Hedge's g; CI=95% Confidence Interval; σ^2= Population Standard Deviation; Q= Cochrane's Q; n=number of effects

Table 2.

Meta Statistics for overall, subdomain and exploratory analyses.

	g	CI	σ^2	Q	n
			All Tasks		
Overall EF	1.29*	1.12, 1.47	2.23	1,629.01*	438
Inhibition	1.64*	1.33, 1.95	4.06	1,312.56*	228
Updating	0.80*	0.68, 0.92	0.23	296.61*	223
Shifting	1.40*	1.02, 1.79	5.08	1,121.55*	174
Processing Speed	1.50*	1.19, 1.80	3.42	1,036.67*	183

Note. * p<.001; g= Hedge's g; CI=Confidence Interval; σ^2= Population Standard Deviation; Q= Cochrane's Q; n=number of effects

Figure 1. Flowchart displaying progression of article elimination.

Figure 2. Effect sizes (n=21) for EF differences between YA and OA by task. Positive numbers indicate that YA performed better. Negative effect sizes indicate OA performed better. Tails indicate 95% confidence intervals.

Note. ** p<.001 in accordance to a Bonferroni correction; * p<.05 uncorrected; Blue=Inhibition, Green=Updating, Red=Shifting.

Figure 3. (A) Effect sizes for EF differences between YA and OA for overall EF (n=438) and for inhibition (n=228), updating (n=223), shifting (n=174), and processing speed (n=183) subdomains.