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Claremont Graduate University

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Approval of the Dissertation Committee

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Abstract

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The healthy development of executive function in adolescents is essential for controlling attention and behavior, especially as children confront the challenges associated with puberty, social situations, parental pressures, academic pursuits, and the transition to adulthood. For children prenatally exposed to teratogenic substances (i.e., certain prescription medications, maternal infections or conditions, alcohol, tobacco, etc.), higher-order cognitive skills may be compromised, resulting in an increased risk of delayed developmental functioning, deficits in cognitive and executive functioning, and poorer academic outcomes. Research findings suggest that even low-to-moderate levels of alcohol and/or tobacco use during pregnancy are associated with poorer academic performance, lower IQ scores, and reduced performance on various cognitive tasks. This more common, yet less understood and under-reported, low-to-moderate level of substance use is an area of growing concern.

To that end, using data from the Adolescent Brain Cognitive Development Study (ABCD, 2021), this dissertation explored the association between low-to-moderate prenatal alcohol and/or tobacco exposure and adolescents' subsequent executive function and academic performance at two separate time points in their development. The study examined whether prenatal teratogen exposure (i.e., parent-reported alcohol and/or tobacco use) was associated with negative effects on adolescents' performance on various executive function tasks from the NIH Toolbox-Cognition Battery and/or their average grades in school. Furthermore, given that executive function has not been consistently defined within the psychological literature, with the field of developmental psychology defining executive

function more broadly (i.e., cognitive flexibility, working memory, and inhibitory control; see Diamond, 2013; Zelazo, 2015) and cognitive psychology defining executive function more narrowly (i.e., viewing working memory as a higher-level, superordinate construct that is separate from executive function; see Conway & Engle, 1994; Conway et al., 2021), this study also examined executive function from these competing perspectives. Additionally, the study used a longitudinal approach to explore the role of *timing* in any associations between teratogen exposure and cognitive outcomes, analyzing data from two separate collection periods: baseline and 2-year follow-up.

The overarching hypothesis was that low-to-moderate prenatal substance exposure would be associated with reduced executive function task performance and reduced average grades at both baseline and the 2-year follow-up, with a greater reduction in executive function task performance in the broadly defined models of executive function (relative to the narrowly defined models of executive function). Three separate studies, distinguished by types of prenatal exposure (i.e., Study 1: alcohol, Study 2: tobacco, or Study 3: combined alcohol AND tobacco), explored this overarching prediction using path analyses.

For Studies 1 (alcohol) and 2 (tobacco), these hypotheses were not supported; no significant relationships were detected between low-to-moderate prenatal alcohol or tobacco exposure and either executive function or average grades. In contrast, the results of Study 3 (combined alcohol AND tobacco) presented mixed findings in terms of supporting the hypothesis. Prior to controlling for demographic variables, prenatal combined exposure was negatively associated with the broad definition of executive function at baseline and with average grades at the 2-year follow-up. These findings suggest that prenatal exposure to both alcohol AND tobacco had a small, but significant negative effect on both academic outcomes and executive function when broadly defined.

An important aspect of this study explored executive function from two theoretical perspectives (i.e., developmental versus cognitive psychology). Analyses from these two perspectives yielded a

recurring finding related to the importance of working memory, specifically as an effective predictor of academic performance. By deconstructing executive function, this study offers a novel approach to exploring the cognitive abilities measured in the ABCD Study and has provided new insights into the connection between working memory, executive function, academic performance, and prenatal teratogen exposure.

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I would like to thank my advisor, Dr. Andrew R. A. Conway, for his steadfast support, helpful feedback, and remarkable patience and kindness. I am also extremely appreciative of his deep knowledge in the areas of executive function, working memory, and statistics, all of which were incredibly valuable throughout this process. I would also like to thank Dr. Kathy Pezdek for encouraging me to apply to the Cognitive Psychology Program and always being an unwavering source of support and encouragement. Additionally, I appreciate the kind support and excellent feedback of my other committee members, Dr. Lise Abrams and Dr. Philip David Zelazo.

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Table of Contents

Abbreviations

Abbreviation	Term
ABCD Study	Adolescent Brain Cognitive Development Study
CAT	Computer-adaptive testing
CDC	Centers for Disease Control and Prevention
DCCS	Dimensional change card sort
EF	Executive function
EF-Broad	Executive function-Broad
EF-Narrow	Executive function-Narrow
EFA	Exploratory factor analyses
FAS	Fetal alcohol syndrome
FICA	Flanker inhibitory control and attention
IRT	Item response theory
L2M	Low-to-moderate
LSWM	List sorting working memory
NIH	National Institutes of Health
NIHTB-CB	NIH Toolbox-Cognition Battery
ORR	Oral reading recognition
PAE	Prenatal alcohol exposure
PCPS	Pattern comparison processing speed
PFC	Prefrontal cortex
PSMT	Picture sequence memory test
PTE	Prenatal tobacco exposure
PVT	Picture vocabulary test
SES	Socioeconomic status
T1	Time 1, baseline collection period
T2	Time 2, 2-year follow-up collection period
WM	Working memory

Note. Common abbreviations used throughout the manuscript.

1. Introduction

Throughout childhood, most individuals begin to develop a set of self-regulatory, goal-directed behaviors that are essential for attention and concentration (Diamond, 2013; Zelazo, 2015). However, the development of these top-down, higher-order cognitive skills may be compromised for children who are prenatally exposed to a variety of teratogens, such as certain prescription medications, maternal infections or conditions (e.g., pre-gestational diabetes), recreational/illicit drugs, alcohol, or tobacco (Anderson & Choonara, 2007; Fine et al., 2019; Fryer et al., 2012; Hughes, 2011; Mayes et al., 2005; Vaglenova et al., 2004). A teratogen is defined as a substance "that may produce physical or functional defects in the human embryo or fetus after the pregnant woman is exposed to the substance," (Tantibanchachai, 2014) potentially resulting in birth defects, abnormalities in function or structure, growth inhibition, or termination of the embryo or fetus (CDC, 2015; Genetic Alliance, DC Dept. of Health, 2010; Webb, 2017). The use of teratogenic substances during pregnancy persists as a significant public health issue, presenting risks to fetal development, creating socioeconomic burdens due to the increased need for social and medical assistance, and contributing to long-term effects on cognitive and behavioral outcomes in the exposed child (Ross et al., 2015; Sithisarn et al., 2012; Zazo et al., 2021). The fetal period of development is extremely vulnerable to both alcohol and tobacco exposure, with even a small amount of exposure associated with an increased risk of developmentally delayed functioning, including deficits in interpersonal skills, motor skills, intellectual abilities, cognitive and executive functioning (EF), and academic outcomes (Polańska et al., 2015).

The potentially long-term effects of prenatal substance use on the development of EFs is an area of particular concern given that EFs are considered predictors of various life outcomes (Diamond, 2013; Zelazo & Carlson, 2012; Zelazo & Carlson, 2020). For instance, EFs are essential for school readiness and are considered more important than IQ scores or entry-level math or reading (Diamond, 2013; Zelazo & Carlson, 2012; Zelazo & Carlson, 2020). Additionally, EFs tend to predict both math and reading scores

throughout a child's school years (Diamond, 2013; Zelazo & Carlson, 2020). Essentially, children struggling with EF skills tend to struggle academically, and these challenges are positively correlated with other life outcomes, such as physical and mental health, professional success, marital harmony, and public safety (Diamond, 2013; Zelazo & Carlson, 2012).

Further examining the relationship between prenatal substance exposure and EF/academic outcomes is critical if effective interventions are to be implemented. To that end, the first section of this paper provides a review of the literature assessing the potentially harmful impact of prenatal substance exposure, particularly low-to-moderate alcohol and/or tobacco exposure, on children's EF development and academic outcomes. The first portion of this review focuses on the following: (a) prenatal teratogen exposure, specifically low-to-moderate alcohol exposure, tobacco exposure, and concurrent exposure to both alcohol and tobacco; and (b) a brief overview of EF and its importance in academic outcomes. The second portion of the review explores: (c) standardized measures of EF using the NIH Toolbox-Cognition Battery (NIHTB-CB); and (d) an introduction to the Adolescent Brain Cognitive Development (ABCD) Study.

1.1. Prenatal Teratogen Exposure

As late as the 1960s, the primary causes of abnormal/atypical development in infants were not known, and this included the potential effects of teratogenic substances on embryonic and fetal development (Armstrong, 1998; Crain & Bennett, 1996). While researchers had concerns about fetal and embryonic exposure to substances by the 1950s (based on the prevalence of specific birth defects attributed to thalidomide, a common morning sickness treatment; see Vargesson, 2015), it was not until 1973 that a group of American dysmorphologists (i.e., pediatricians trained on the causes, treatment, and prevention of birth defects) reported on and coined the term Fetal Alcohol Syndrome (FAS) (Armstrong, 1998; Jones et al., 1973), prompting the Centers for Disease Control and Prevention (CDC) to launch the nation's first monitoring program for birth defects (Armstrong, 1998). This seminal work

(Jones et al., 1973) highlighted the need to redefine societal perceptions of maternal alcohol consumption (O'Neil, 2011). It also pioneered the way for research exploring the effects of other potentially teratogenic substances on embryonic and fetal development (i.e., tobacco, illicit drugs, medications, etc.). Over the past 50 years, this research has led to significant discoveries, including findings that suggest that the effects of maternal substance use during gestation may have long-lasting cognitive, developmental, behavioral, and psychological consequences for their offspring (Anderson & Choonara, 2007; Fine et al., 2019; Fryer et al., 2012; Hughes, 2011; Mayes et al., 2005; Vaglenova et al., 2004).

For example, recent studies have shown that exposure to excessive levels of alcohol are positively correlated with both premature birth and moderate to large impairment of cognitive performance (including long-lasting deficits in EF) and diminished brain volume (Fryer et al., 2012; Hughes, 2011). Likewise, compared to children of nondrinkers, children prenatally exposed to alcohol (even limited use) exhibited significant deficits in intellectual functioning (e.g., short-term memory and encoding), academic skills (e.g., math and reading), and growth parameters (Coles et al., 1991; Lees et al. 2020). Additional studies demonstrated that tobacco use during pregnancy may have negative effects on prenatal and postnatal development, including the production of sensory, cognitive, and motor deficits among infants and toddlers (Anderson & Choonara, 2007; Vaglenova et al., 2004). Moreover, socioeconomic differences appear to play a role in prenatal substance use, with low-to-moderate alcohol consumption related to higher socioeconomic status and tobacco use associated with lower socioeconomic status (Römer et al., 2020).

In addition, studies examining maternal use of illicit drugs (e.g., amphetamines, cannabinoids, cocaine, LSD, opiates, etc.) and prescription medications (e.g., anticonvulsants, anti-anxiety drugs, antidepressants, anti-psychotics, etc.) during pregnancy have revealed developmental delays in offspring, including difficulties processing information, decreased inhibitory response and sustained

attention, and poorer performance on spatial tasks and reactions to visual stimuli (Anderson & Choonara, 2007; Mayes et al., 2005). Another study by Piper et al. (2011) reported that 7- to 9-year-olds prenatally exposed to methamphetamine or multiple substances (i.e., some combination of exposure to methamphetamine and alcohol, nicotine, or marijuana) exhibited more problems with metacognition and behavior regulation, but only subtle spatial performance issues, and no effect on IQ, spatial span, or other cognitive tasks. While research on the potential effects of prenatal maternal polysubstance use (i.e., using more than one substance) is still in its early stages, a common thread found in each of these studies is the negative relationship between teratogen exposure and the normal development of cognitive function from infancy through adolescence. Because the prenatal and early postnatal growth stages are critical periods of development, studies examining the relationship between in utero teratogen exposure and subsequent development suggest that cognitive and behavioral deficiencies with origins in these developmental periods may persist throughout childhood and into adolescence (Fryer et al., 2012; Vaglenova et al., 2004).

During gestational development, the timing of teratogenic exposure is important (Crain & Bennett, 1996). For instance, the embryonic period between the third and eighth weeks of pregnancy is widely considered the most sensitive period for producing structural birth defects. While the fetal period between the ninth week through birth is not *as* vulnerable to structural teratogenic birth defects, prenatal exposure to teratogens may cause harm to the brain and spinal cord at any time during pregnancy, possibly leading to structural (e.g., reduced head circumference), neurological, or functional (e.g., cognitive/intellectual deficits) abnormalities of the central nervous system (Crain & Bennett, 1996; Ekblad et al., 2015; Källen, 2000; NCBDDD et al., 2004; Sadler, 2011).

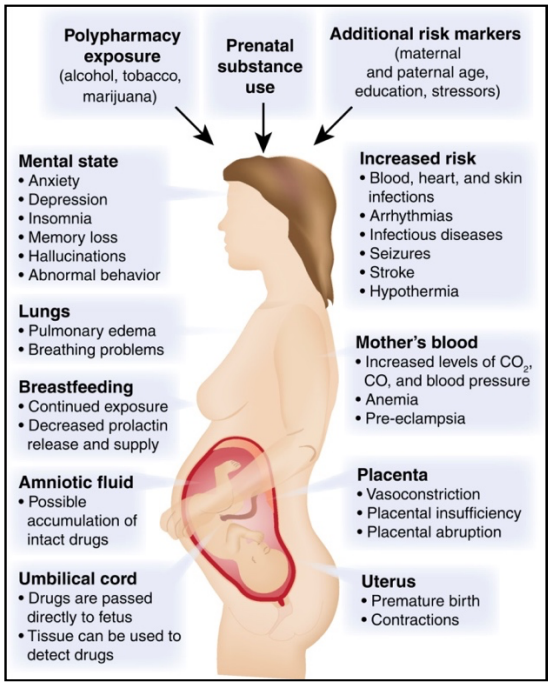
Although a great deal of scientific evidence supports the negative association between heavy alcohol/tobacco exposure and fetal development, and the potentially longer-term effects on childhood outcomes (Anderson & Choonara, 2007; Fine et al., 2019; Fryer et al., 2012; Hughes, 2011; Mayes et al.,

2005; Sithisarn et al., 2012; Streissguth et al., 1999; Vaglenova et al., 2004), the majority of pregnant women are not heavy users (Römer et al., 2020; Zuccolo et al., 2013). The more prevalent occurrence, and an area of growing concern, is low-to-moderate alcohol and/or tobacco use during pregnancy (Maya-Enero et al., 2021; Negrão et al., 2021; Olson et al., 1997; Polańska et al., 2015; Römer et al., 2020; Todorow et al., 2010; Zuccolo et al., 2013). This lower level of substance use is typically under-reported and less understood (Römer et al., 2020; Zuccolo et al., 2013), but may have subtle, yet important consequences for fetal and child development outcomes (Maya-Enero et al., 2021; Negrão et al., 2021; Olson et al., 1997; Polańska et al., 2015; Römer et al., 2020; Todorow et al., 2010; Zuccolo et al., 2013).

Teratogenic substance use during pregnancy may alter a developing fetus through a wide range of mechanisms (see Figure 1; Ross et al., 2015). For instance, a substance may cross the placenta (which is a common occurrence for most drugs, including alcohol and tobacco), allowing the substance to have direct access to the fetus (Goodlett et al., 2005; Huizink & Mulder, 2006; Ross et al., 2015; Sithisarn et al., 2012). Prenatal substance exposure may also have direct effects on the placenta and/or the uterus, potentially altering placental secretions and/or blood flow to the fetus, and thereby having an indirect effect on the fetus (Goodlett et al., 2005; Huizink & Mulder, 2006; Ross et al., 2015; Sithisarn et al., 2012). The specific details of each of these biological processes is beyond the scope of this review, but understanding the neurological mechanisms associated with prenatal teratogen exposure is essential in understanding the potential effects that this exposure may have on the normal development of EF. For this reason, a brief overview of the mechanisms by which prenatal alcohol and/or tobacco use may affect neurological functioning is included in each of the sections below. Following the discussion of these neurological mechanisms, an overview of the literature examining the behavioral evidence associated with prenatal substance exposure and various child cognitive/academic outcomes is included.

Figure 1

Biological Targets of Prenatal Teratogen Exposure



Note. Teratogenic substances may directly target the developing fetal brain. These substances may also reach the fetus through a variety of maternal organs, including the uterus, heart, placenta, lungs, and brain. From "Developmental Consequences of Fetal Exposure to Drugs: What We Know and What we Still Must Learn," by E.J. Ross, D.L. Graham, K.M. Money, and G.D. Stanwood, 2015, *Neuropsychopharmacology Reviews*, *40*, p. 62. Copyright 2015 by Springer Nature Limited.

1.1.1. Prenatal Alcohol Exposure

Neurological Mechanisms. Prenatal alcohol exposure (PAE) may affect the developing fetus via a variety of proposed mechanisms, including damage to the mitochondria, effects on glial cells, effects on the developing neurotransmitter systems, oxidative stress, effects on astrocytic structure and functions, effects on cell adhesion, interference in gene expression, and brain glucose utilization disruption (Sithisarn et al., 2012). Potential consequences associated with damage to, or disruption of, these processes include apoptosis, cell necrosis, or cell death (Sithisarn et al., 2012). Additionally, human studies of PAE have shown modifications in regions of the brain associated with EF and working memory

(WM), including the hippocampus and prefrontal cortex (PFC), with animal models showing decreased neural plasticity within the PFC following PAE (Uban et al., 2020).

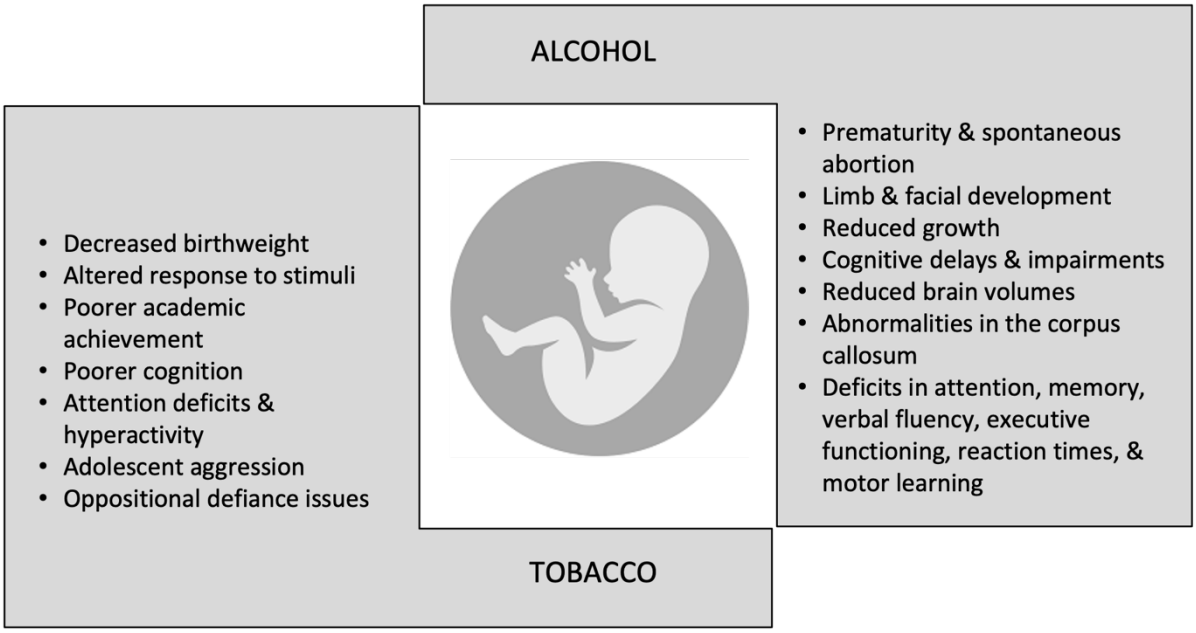
Moreover, recent studies have demonstrated that even a moderate blood level of alcohol may be associated with "a high frequency of neural tube midline defects" early in development, leading to atypical development of the nervous system (Huizink & Mulder, 2006, p. 33). This abnormal development may contribute to subtle deficits in neurodevelopment (Huizink & Mulder, 2006). Further, other studies have determined that even low amounts of PAE may affect serotonergic neuron development and that exposure to ethanol may disrupt growth of glia and neuronal precursors that are essential to the development of the nervous system (Ross et al., 2015). In studies with rodents examining the effects of PAE, exposure to alcohol continues to have powerful effects on postnatal brain development (Ross et al., 2015).

Behavioral Evidence. Prenatal consumption of alcohol during pregnancy has been associated with a variety of negative outcomes in exposed children, including social and emotional development issues, hyperactivity difficulties, and behavioral and cognitive deficits (see Figure 2; Anderson & Choonara, 2007; Fine et al., 2019; Fryer et al., 2012; Hughes, 2011; Mayes et al., 2005; Polańska et al., 2015; Ross et al., 2015; Sithisarn et al., 2012; Streissguth et al., 1999; Vaglenova et al., 2004). At the more extreme end of the continuum of effects of PAE is fetal alcohol *syndrome*, characterized by severe short-term and long-term developmental, neurocognitive, behavioral, and growth deficits (Polańska et al., 2015; Streissguth et al., 1999). The more common, but less understood, level of prenatal maternal alcohol use is low-to-moderate consumption. Although inconsistencies exist throughout the literature, low-to-moderate alcohol use is typically defined as 1-2 units of alcohol per week (i.e., less than four drinks per week) at the low end of the spectrum and no more than 3-6 units per week (i.e., five to eight drinks per week) at the moderate end of the spectrum (Polańska et al., 2015). To date, fewer studies

have explored the potential effects of low-to-moderate prenatal alcohol use, with mixed, inconsistent, and conflicting findings (Todorow et al., 2010).

Figure 2

Summary of Potential Effects of Prenatal Alcohol and Tobacco Exposure on Offspring Development



Note. Fetal exposures to teratogenic substances may induce a wide range of significant structural and neurobehavioral deficits. As discussed in this paper, the timing, dose, and duration of use all play a role in determining the long-term effects on the developing child. Adapted from "Developmental Consequences of Fetal Exposure to Drugs: What We Know and What we Still Must Learn," by E.J. Ross, D.L. Graham, K.M. Money, and G.D. Stanwood, 2015, *Neuropsychopharmacology Reviews*, *40*, p. 77. Copyright 2015 by Springer Nature Limited.

For example, researchers investigating the effects of prenatal low-to-moderate alcohol exposure on cognitive outcomes and school performance at 11 years of age found that maternal drinking up to one unit of alcohol per day was not associated with reduced academic outcomes (i.e., performance on the United Kingdom National Curriculum Tests, covering science, mathematics, and English) at age 11 Alati et al. (2013). However, moderate drinking of four units or more of alcohol in a single drinking event was associated with lower academic performance in the offspring, and lower IQ scores in univariate analyses. Similarly, Zuccolo et al. (2013) examined the relationship between moderate PAE and

cognitive/educational performance of offspring at ages 8 years and again at 11 years of age using data from the Avon Longitudinal Study of Parents and Children (ALSPAC). In this study, self-reported prenatal drinking was associated with *higher* offspring IQ scores at age 8 and *better* academic performance at age 11 when compared to unexposed peers. However, these relationships were weakened after accounting for socioeconomic status and other confounding variables. Further, Lees et al. (2020) analyzed baseline data from the Adolescent Brain Cognitive Development (ABCD) Study and found that PAE of any severity was related to increased psychopathology, internalizing and externalizing behaviors, and impulsivity in children ages 9 to 11 years, with some notable dose-specific relationships. For instance, heavier PAE was associated with attention deficits, aggression/rule-breaking, and depressed/withdrawn behavior. Surprisingly, these researchers also reported that, compared with unexposed peers, low alcohol exposure early in pregnancy was associated with *better* inhibitory and attention capabilities.

In contrast to the above findings, Mamluk et al. (2017) conducted a meta-analysis exploring the relationship between low prenatal alcohol consumption and various childhood outcomes, finding that even light exposure was related to offspring being classified as small for gestational age and at a greater risk of preterm delivery. And in a review examining risk factors for poor child neurodevelopment related to low or moderate PAE, Polańska et al. (2015) reported that moderate alcohol use in the first and second trimesters was associated with lower composite scores (i.e., verbal, quantitative, visual/abstract subscales) among African American children around the age of 10 years, with lower IQ scores at 15 years of age. Finally, in an effort to examine the potential effects of low-to-moderate PAE in 5-year-olds, Jensen et al. (2015) investigated grapho-motor skills using the Draw-A-Person (DAP) task; these researchers reported that children exposed to moderate levels of alcohol scored on average 6 points lower (on a scale of 0 to 49) compared to their unexposed peers. Of significant concern is that over the course of development and as children are exposed to more demanding cognitive tasks, gaps such as this will widen and perhaps expand to other areas, such as more challenging assembly tasks or learning

to write. To that end, a 14-year study in Seattle assessed longer-term behavior and learning effects of lower levels of alcohol exposure in utero. In this study, no alcohol-related deficiencies were reported at 8 months or at 7 years of age (Olson et al., 1997), but by age 14 years, the adolescents demonstrated alcohol-related behavioral and cognitive dysfunctions similar to those found in studies focused on children of alcoholics, including deficits in sustained attention, spatial memory, response inhibition, speed versus accuracy tradeoff, and difficulties with various academic skills.

Of course, there are important factors to consider when interpreting these inconsistent findings. For instance, the teratogenic effects of alcohol use depend on the timing of exposure (i.e., early or late in pregnancy), the dose, the duration of consumption, and the individual constitution of the mother and the fetus, particularly in terms of alcohol metabolization (Maya-Enero et al., 2021; Polańska et al., 2015; Roffman et al., 2021). Additionally, retrospective self-reporting of prenatal maternal consumption is problematic and may lead to misclassification (Polańska et al., 2015). Furthermore, inconsistent findings are likely due to the inherent methodological limitations in this area of research, such as underreporting of maternal consumption due to social stigmas, retrospective recall bias, the impossibility of random assignment to treatment groups, and the numerous confounding variables associated with child development, including socioeconomic status and maternal education (Huijbregts et al., 2006; Todorow et al., 2010). Many of the studies referred to in this review employed multivariate analyses to control for a variety of potential confounders. Nevertheless, more research is needed using large samples of a diverse population of mothers and their offspring for a better understanding of this under-explored domain of teratogenic exposure, and more specifically examining the long-term developmental effects on cognitive function and academic performance (Negrão et al., 2021; Polańska et al., 2015).

1.1.2. Prenatal Tobacco Exposure

Neurological Mechanisms. The effects of prenatal tobacco exposure (PTE) have been associated with numerous biological mechanisms. Specifically, the nervous system appears to be particularly

vulnerable to tobacco during the fetal/neonatal period through infancy (Julvez et al., 2007). Levels of nicotine in the fetus have been observed to be higher than maternal levels of nicotine by 15%. Given that nicotine has been associated with reduced uterine blood flow to the placenta (causing a prolonged reduction in oxygen and nutrients), this level of fetal nicotine exposure has raised concerns about the normal development of the fetal brain (Julvez et al., 2007). Additionally, "nicotine interacts with nicotinic acetylcholine receptors (nAChRs)," which appears to affect the cerebellum, frontal cortex, and hippocampus (where a large number of these receptors may be present during pregnancy) (Julvez et al., 2007, p. 830). nAChRs activation in rodents affects spontaneous neural activity, morphogenesis, and neuronal survival (Thompson et al., 2009). Prenatal nicotine exposure may also disrupt the cholinergic system that is responsible for regulating important aspects of brain function, potentially leading to cognitive function impairment and a reduction in cognitive processing (Thompson et al., 2009).

Further, studies using neuroimaging suggest that PTE may have the following effects on brain development: "thinner para-hippocampal, middle frontal, and orbitofrontal cortices, reduced cortical gray matter and parenchymal volumes, a smaller head circumference, and increased fractional anisotropy (FA) in anterior cortical white matter but decreased FA in supplementary motor area and premotor cortex, suggesting that exposure affects white matter maturation" (Bennett et al., 2013, pp. 49-50). For example, in a study using fMRI with 12-year-old children with PTE, the inferior parietal regions showed greater activation during a N-back WM task when compared to their unexposed peers (Bennett et al., 2013). Studies with non-human mammals have also provided valuable insight into some of the fundamental molecular mechanisms associated with PTE (Ross et al., 2015). For instance, learning, memory, and sensory processing deficiencies have been observed in rodents with PTE, and PTE during pregnancy and breast-feeding has been associated with increased glia, decreases in cell size, and neuronal cell loss in non-human primates (Ross et al., 2015). Finally, juvenile and adult rats that experienced PTE exhibited "changes to spine density, dendritic length, and dendritic branching" (Ross et

al., 2015, p. 74). Changes such as these may affect the developmental trajectory of the brain and other organs, contributing to later dysfunction, including increased internalizing and externalizing behaviors, decreased receptive language skills, deficits in visuospatial memory, poorer performance on cognitive tasks, and attention deficits (Ross et al., 2015).

Behavioral Evidence. Unlike the inconsistent findings associated with low-to-moderate prenatal alcohol consumption, the literature examining the effects of PTE is less ambiguous, with even low active (i.e., maternal smoking) or passive (i.e., secondhand smoke) prenatal exposure contributing to neurodevelopmental problems in children, particularly related to poorer academic performance and an increased prevalence of behavior-related issues (see Figure 2 above; Banderali et al., 2015; Oh et al., 2021; Polańska et al., 2015). Similar to alcohol exposure, the negative effects of PTE depend on the timing of the exposure (i.e., first, second, or third trimester) and the associated dose (Banderali et al., 2015; Ross et al., 2015), with prenatal exposure to maternal and/or paternal/environmental smoking increasing the likelihood of preterm birth, offspring being classified as small for gestational age and/or low body weight, as well as various birth defects (Drake et al., 2018). As of 2016, the CDC indicated that 7.2% of women reported smoking throughout pregnancy, with prenatal smoking most prevalent among non-Hispanic American Indian or Alaska Native women (16.7%), women between 20-24 years old (10.7%), and women with a high school education (12.2%) or less (11.7%) (Drake et al., 2018). In addition, approximately half of pregnant non-smokers were exposed to passive, secondhand smoke (Polańska et al., 2015). These statistics and the data on negative outcomes associated with PTE reinforce the importance of prenatal care, including substance use education and smoking cessation interventions, especially among young women from particular demographic groups.

According to the National Cancer Institute (2021), tobacco smoke contains over 7,000 different chemicals, with at least 250 of those chemicals known to be toxic and/or carcinogenic. Nicotine serves as one of the primary ingredients in tobacco smoke and transfers easily through the placenta, with fetal

concentrations often higher than those found in maternal blood. Exposed newborn infants typically exhibit more irritability, reduced attention, increased startle responses, and poorer self-regulation than their unexposed peers (Ross et al., 2015; Sithisarn et al., 2012). Research on prenatal exposure to tobacco smoke and nicotine is expansive, with studies reporting numerous negative longer-term child and adolescent outcomes, including developmental deficits related to fetal growth (e.g., low birth weight), brain development (e.g., reduced brain size and head circumference), physiology (e.g., obesity, cardiovascular, respiratory), behavior (e.g., conduct disorders, internalizing, externalizing), and most relevant to this review, cognition (e.g., attention and language deficits, poorer academic performance) (Banderali et al., 2015; Julvez et al., 2007; Ross et al., 2015).

For instance, in a study examining data from the Quebec Longitudinal Study of Children's Development, researchers found a negative relationship between maternal prenatal smoking and scores on tasks related to memory and intelligence in their offspring (Polańska et al., 2015). Similarly, Julvez et al. (2007) assessed maternal smoking during pregnancy and the subsequent effects on cognitive development in their offspring; these researchers reported that active PTE (smoking at least one cigarette per day throughout pregnancy) was associated with lower global cognitive scores in offspring at 4 years of age. Additional studies have found similar relationships between PTE and cognitive functioning, including attention deficits in children at 6 years of age that extended into later adolescence (Bennett et al., 2009; Cornelius et al., 2007; Cornelius et al., 2011; Jacobsen et al., 2006; Kotimaa et al., 2003; Langley et al., 2007; Lindblad & Hjern, 2010); decreased receptive language abilities in 6-year-old children (Fried et al., 1992; Fried & Watkinson, 1990; Lewis et al., 2007); reduced academic performance and poorer cognitive scores compared to unexposed peers (Agrawal et al., 2010; Bennett et al., 2013; Fried et al., 1992; Fried & Watkinson, 1990); and deficits in sensory processing and visuospatial memory in 16- to 18-year-olds (Jacobsen et al., 2006). These findings suggest that PTE may be associated with

numerous potentially detrimental, long-term effects on cognitive development outcomes starting in infancy and continuing into adolescence and beyond.

1.1.3. Prenatal Concurrent Alcohol and Tobacco Exposure

Neurological Mechanisms. Given that consumption of alcohol and tobacco are frequently connected, distinguishing between the possible effects of one or the other on various fetal developmental processes/outcomes is often challenging (Sabra et al., 2018). As previously discussed, both PAE and PTE may have direct effects on the development of the fetal brain and nervous system, with alcohol exposure potentially disrupting brain growth by interfering with the production of neuroendocrine hormones, and tobacco exposure reducing blood flow to the uterus, depriving the fetus of necessary oxygen and nutrients (Polańska et al., 2015). Further, given that ethanol and tobacco-related substances travel freely through both the placenta and the blood-brain barrier of the fetus, studies have shown that the fetus experiences greater exposure to these substances than does the mother, causing impairment of cell proliferation, hypoxia, and harmful effects to the development of the placenta (Sabra et al., 2018; Wickström, 2007). Lastly, as mentioned below, the combination of these substances may result in a synergistic effect, increasing the risk of low birth weight and growth restriction (Odendaal et al., 2009).

Behavioral Evidence. Prenatal exposure to teratogenic substances often occurs concomitantly, with fetuses exposed to both alcohol and tobacco in utero (Negrão et al., 2021). Exposure to both of these substances increases the risk of premature birth, low birth rate, and intrauterine growth restrictions, with the increased odds resulting in a synergistic effect, whereby the consequences of the combined exposure are more than the sum of the effects of drinking and smoking independently (Dew et al., 2007; Odendaal et al., 2009; Sabra et al., 2018). Evidence of this synergistic relationship was reported by Dew et al. (2007), who conducted a retrospective cohort study examining the prevalence of preterm births in 83,685 live births to mothers in Kansas City, Missouri from 1990–2002. Dew et al.'s

analysis revealed that prenatal smoking alone was associated with a 22% increase in the probability of a preterm birth, and prenatal alcohol consumption alone increasing the odds of a preterm birth by 8%. When used in combination, prenatal alcohol use and smoking together were associated with a 46% increase in preterm births, demonstrating the effects of the harmful interaction between these two substances on gestational age at birth.

According to the CDC (2020), polysubstance use during pregnancy is not uncommon (SAMHSA, 2018). Yet very little is known about how the combined use of tobacco and alcohol during pregnancy may be related to cognitive outcomes in offspring, as compared to their unexposed peers or peers exposed to only one of these substances (Dew et al., 2007; Negrão et al., 2021). Given the lack of research dedicated to low-to-moderate prenatal alcohol and/or tobacco use during pregnancy, more studies are needed to understand how exposure to these substances in utero may be related to overall cognitive development, and more specifically, executive function (EF), where atypical development may compromise academic performance and other long-term outcomes. To that end, the next portion of this review will: (a) provide a brief overview of EF and its importance in academic outcomes; (b) examine the brain areas associated with EF; and (c) identify which of those EF-associated brain areas are also affected by PAE/PTE. Understanding these shared brain areas is essential if researchers are to determine the mechanisms by which prenatal exposure to these substances may ultimately impair EF and academic performance.

1.2. Executive Function

Though widely referenced throughout the literature, EF is defined in a variety of different ways depending on the specific area of psychology referring to this construct. More specifically, most of the research on EF appears to be centered within three domains of psychology: (a) neuropsychology, (b) individual differences in adult cognition, and (c) developmental psychology. Given that this review is focused on the relationship between prenatal substance exposure and its subsequent effects on the

development of EF, this review will employ the definition of EF used throughout the developmental psychology literature.

In the developmental psychology literature, EF refers to a top-down, neurocognitive set of self-regulatory skills that are essential for controlling attention and behavior (Zelazo, 2015; Zelazo & Carlson, 2012). When our automatic mental processes are confronted with a novel stimulus or a complex cognitive task requiring focused attention, EF abilities are recruited into action. These skills are measured behaviorally as (a) cognitive flexibility, (b) working memory, and (c) inhibitory control (Diamond, 2013; Zelazo, 2015). Cognitive flexibility facilitates the process of task-switching, which assists in transitioning attention easily and quickly, adapting to changing demands, and thinking creatively (Diamond, 2012, 2013; Zelazo, 2015). Working memory involves both storage and processing of information, which aids in keeping information in one's mind as well as manipulating it in some way in order to use that information later. Working memory is particularly useful for connecting one idea to another idea, and relating something one has previously read, learned, or heard to something one is presently experiencing. It also assists with performing math calculations in one's head, comprehending cause and effect situations, and remembering instructions with multiple steps, permitting the performance of those steps in the right order (Diamond, 2012, 2013; Zelazo, 2015). Finally, inhibitory control (also known as self-control and self-regulation) assists in controlling one's attention, thoughts, emotions, and/or behavior in an intentional way, so as to ignore the urge to act on impulse. It also helps one to stay focused even when bored or tempted by distractions (Diamond, 2013; Zelazo, 2015). Longitudinally and statistically, children with less self-regulation grow up to be adults exhibiting poorer health, making less money, and engaging in more criminal activities (Diamond, 2013; Moffitt et al., 2011; Zelazo, 2015). These three core EFs—working memory, cognitive flexibility, and inhibitory control—also serve as the foundation for developing higher order executive processes, including planning, reasoning, and problem solving, which are essential for, among other things, academic success (Diamond, 2013).

Taken together, normal development of EF is essential for adolescents as they navigate puberty, social situations, academic challenges, parental pressures, and the transition to adulthood (Diamond, 2013; Moffitt et al., 2011). Evidence suggests that individual differences exist in the development of EF during childhood (Blair et al., 2005; Hughes, 2011; Zelazo, 2015). These differences tend to predict variations in developmental and social outcomes, including physical and mental health; school readiness and academic achievement; professional and relationship success; and overall quality of life (Blair & Razza, 2007; Diamond, 2013; Zelazo, 2015). Given that EFs are considered critical skills that are essential for success (e.g., self-control, creativity, discipline, flexibility; Diamond, 2013), mastering these skills can have profound and life-altering impacts on all aspects of one's life, meaning that anything that causes damage to, or impairment of, these cognitive processes (e.g., prenatal substance exposure) could cause severe problems in everyday functioning (Miyake et al., 2000).

To that end, much of the developmental psychology literature has focused on the relationship between EF and *typical* psychological, social, and cognitive development (Diamond, 2013). But there is a lack of research on *atypical* development as it relates to EF abilities and academic outcomes, particularly among children prenatally exposed to low-to-moderate levels of alcohol and/or tobacco (Blair & Razza, 2007; Diamond, 2013; Zelazo, 2015). To better understand the relationship between PAE/PTE and the subsequent development of EF, it is important to identify the brain areas that are associated with EF abilities, as well as those brain areas that are also affected by PAE/PTE; this would help researchers to design tasks that effectively target these shared brain areas.

1.2.1. Brain Areas Associated with Executive Function

The prefrontal cortex (PFC) has a variety of functions, but it is especially critical in the planning of novel or complex behaviors and is considered one of the primary areas underlying the brain's executive functioning (Reisberg, 2019). Given the importance of the integrity of the PFC for optimal EF performance, damage to, or disruption of, the PFC's normal development (e.g., via prenatal substance

exposure) can have serious consequences for the higher-order cognitive tasks associated with EF (Zelazo et al., 2013). Though WM, inhibitory control, and cognitive flexibility are mostly associated with the same brain areas, there are some differences. Evidence from studies using neuroimaging indicates that various "EF skills activate partially overlapping regions in the brain," suggesting common activation networks across tasks (including dorsal attention and frontoparietal control networks) (Zelazo & Carlson, 2020).

More specifically, in an fMRI study conducted by Lemire-Rodger et al. (2019), adults performed a single cognitive task that was designed to manipulate inhibition, cognitive flexibility, and working memory (controlling for other task-related demands). Results of the study suggested that (a) "working memory was associated with activity in dorsolateral prefrontal, lateral parietal and insular cortices bilaterally"; (b) inhibitory control "engaged right lateral and superior medial prefrontal cortex, inferior parietal lobules bilaterally, right middle and inferior temporal cortex, and ventral visual processing regions"; and (c) cognitive flexibility (or task switching) "was associated with bilateral activity in medial prefrontal cortex, posterior cingulate cortex and precuneus, as well as left inferior parietal lobule, lateral temporal cortex and right thalamus" (Lemire-Rodger et al., 2019, p. 1).

1.2.2. Shared Brain Areas: Executive Function and Prenatal Substance Exposure

Many of the brain areas that seem to be activated when engaged in EF-related tasks, have also been associated with brain areas (and various neurological mechanisms) that appear to be vulnerable to prenatal alcohol and tobacco exposure (see Table 1). For instance, the cerebral cortex controls various higher-level functions, including cognition, WM, language and speech production, hearing and visual perception, and sensorimotor control, with the PFC typically associated with EF (Uban et al., 2020; Zieff & Schwartz-Bloom, 2008). Development of these brain areas occurs throughout gestation, meaning exposure to teratogenic substances may disrupt the normal development of these brain regions that are essential for optimal cognitive development. Further, the cerebellum is typically associated with various

EF-related tasks, such as, task sequencing, cognitive processing, language fluency and acquisition, and estimation and perception of time, making the third trimester a particularly vulnerable period of substance exposure (Huizink & Mulder, 2006; Zieff & Schwartz-Bloom, 2008). Additionally, when the corpus callosum is altered, misshaped, or altogether missing, mild to extensive cognitive impairments have been observed, including deficits in motor functioning and EF (Huizink & Mulder, 2006; Zieff & Schwartz-Bloom, 2008). Gestationally, substance exposure during the first trimester may interfere with the formation of the corpus callosum, and exposure during the second and third trimesters may alter its shape and influence its ability to interact with other cortical neurons (Zieff & Schwartz-Bloom, 2008). Finally, damage to the neuronal circuitry of the hippocampus, particularly during the third trimester, can have profound effects on memory and learning processes (Huizink & Mulder, 2006; Uban et al., 2020; Zieff & Schwartz-Bloom, 2008). Understanding these related brains areas is essential if researchers are to design tasks that effectively target these teratogen-vulnerable brain regions. To that end, the next section of this review briefly discusses a set of standardized EF measures (i.e., the NIH Toolbox-Cognition Battery), designed by a team of developmental cognitive neuroscientists, aimed at targeting these shared brain regions. Immediately following the discussion of these standardized measures is a short introduction to the NIH-sponsored longitudinal study (i.e., the ABCD Study) that is currently using these standardized tasks.

Table 1

Neurodevelopmental Consequences of Prenatal Teratogen Exposure

Substance	Neurochemistry Involved	Neurological Mechanisms Affected	Neurodevelopmental Consequences
Alcohol	GABA and NMDA Blocks NMDA receptor activity and increases GABAergic activity	Damage to the mitochondria Effects on glial cells Effects on the developing neurotransmitter systems Oxidative stress Effects on astrocytic structure and functions Effects on cell adhesion Interference in gene expression	Craniofacial dysmorphologies Decreased birth weight Hyperactivity Cognitive deficits Cortical dysgenesis Cell death Reduced brain volume Apoptosis Cell necrosis

		Brain glucose utilization disruption Decreased neural plasticity in the PFC	
Nicotine	Acetylcholine Activates nAChRs	Affects morphogenesis, spontaneous neural activity, and neuronal survival Disrupts the cortical cholinergic system Thinner para-hippocampal, middle frontal, and orbitofrontal cortices Reduced cortical gray matter and parenchymal volumes Increased fractional anisotropy (FA) in anterior cortical white matter Decreased FA in supplementary motor area and premotor cortex affecting white matter maturation	Decreased birth weight Hyperactivity Cognitive disabilities Emotional disruptions Internalizing and externalizing behaviors Decreased receptive language skills Deficits in visuospatial memory

Note. Adapted from "Prenatal Exposure to Drugs: Effects on Brain Development and Implications for Policy and Education," by B.L. Thompson, P. Levitt, and G.D. Stanwood, 2009, *Nature Reviews Neuroscience*, *10*(4), p. 22. Copyright 2009 by Springer Nature Limited.

1.2.3. Standardized Measures of Executive Function

Historically, researchers have used numerous different assessment tools to examine and measure EF. This lack of standardization complicates the ability to effectively compare outcomes. Additionally, different researchers have used the same task to measure different components of EF. This reflects a long-standing problem in this area of research. Miyake et al. (2000) refer to this as the "task impurity problem," meaning that a specific task may be designed to target one type of EF (e.g., cognitive flexibility), but because EFs require tapping into other cognitive processes as well, it is difficult to know if a task is solely assessing the intended component. For instance, the Wisconsin Card Sorting Test, which is often used to test EF, involves sorting cards based on either shape, color, or number of items displayed on the cards. After a sequence of trials, the sorting dimension changes without warning, requiring the participant to shift to a new sorting rule. Performance on this task reflects not only cognitive flexibility, but also motor, perceptual and other cognitive capabilities, each of which are not

able to be isolated from one another (Friedman et al., 2008). This challenge speaks to the complexity of EF and its role in overall cognition. It also speaks to the need for more standardized tasks that are designed to measure specific aspects of cognition.

Until recently, a valid, reliable toolbox of tasks measuring cognitive and executive functioning was not available. Understanding the need for a battery of standardized cognitive measures, in 2004, the National Institutes of Health (NIH) formed a coalition referred to as the Blueprint for Neuroscience Research, whose goal was to develop resources, tools, and training opportunities "to accelerate the pace of discovery in neuroscience research" (HealthMeasures, 2021). What emerged from this taskforce was a comprehensive, standardized, normed, and validated set of assessment tools that can be used by researchers to examine motor function, sensation, emotion, and cognition (HealthMeasures, 2021). What follows is a brief overview of the NIH Toolbox-Cognition Battery (NIHTB-CB) and the NIH-sponsored study (i.e., the ABCD Study) that is putting this set of measures to use in testing EF (among other cognitive processes).

1.3. The ABCD Study and the NIH Toolbox-Cognition Battery

The Adolescent Brain Cognitive Development (ABCD) Study is the largest longitudinal study on brain development and adolescent health in the United States, following over 11,800 children from pre-adolescence into young adulthood (ABCD, 2021). The baseline data were collected from adolescents between 9.0 and 11.1 years of age and their parents or guardians (Barch et al., 2021). The 2-year follow-up data were collected from adolescents between 10.6 and 13.6 years of age (Barch et al., 2021). The main objective of the ABCD Study "is to produce for the scientific community an informative, high-dimensional data resource, populated by assessments with strong validity and good quality" (Jernigan et al., 2018). To that end, the ABCD Study includes several well-established neurocognitive measures using the NIHTB-CB, which is comprised of seven distinct tasks, five of which are designed to measure aspects of EF (e.g., EF/attention, WM, episodic memory, and processing speed) (HealthMeasures, 2021; Luciana

et al., 2018). The standardized nature of the NIHTB-CB makes it ideal for use in large-scale longitudinal studies like the ABCD Study, and in cross-study comparisons (Weintraub et al., 2013).

1.4. In Summary

In 2020, there were over 3.6 million live births in the United States (CDC, 2022), with approximately 5 percent of pregnant women reporting use of one or more teratogenic substances (National Institute on Drug Abuse, 2020). However, underreporting of substance use during pregnancy is common due to social stigmas, so this is likely an underestimate of actual use (Polańska et al., 2015; Sabra et al., 2018). Even so, this conservative estimate is alarmingly high as it represents over 180,000 children born each year in the United States who may potentially be coping with a variety of lingering biological, structural, developmental, and/or cognitive aftereffects. Prenatal teratogen exposure has been associated with a wide range of behavioral and cognitive deficits (Ross et al., 2015). Children struggling with atypical development of EF also tend to struggle academically (Diamond, 2013; Zelazo & Carlson, 2012), placing them at a further disadvantage when compared to their unexposed peers.

Achieving educational success has been strongly correlated with better overall cognitive well-being in later life (Moorman et al., 2019). However, children who experience atypical development often struggle to achieve the optimal cognitive skills that are necessary for academic success (e.g., language acquisition and EF skills) (Agrawal et al., 2010; Anderson & Choonara, 2007; Banderali et al., 2015; Bennett et al., 2013; Coles et al., 1991; Fried et al., 1992; Fried & Watkinson, 1990; Hackman et al., 2015; Julvez et al., 2007; Lees et al. 2020; Ross et al., 2015; Vaglenova et al., 2004; Zelazo & Carlson, 2020). These challenges have the potential to create and perpetuate life-long academic achievement gaps, which may translate into poorer health, higher stress levels, drug-related problems, and a poverty trap (Diamond, 2013; Moffitt et al., 2011; Zelazo, 2015; Zelazo & Carlson, 2020).

This review has provided a broad overview of the current research on atypical development due to low-to-moderate teratogen exposure and some insights into the potential effects of this exposure on

the development of EF and academic outcomes. The review also explored the shared brain regions and neurological mechanisms associated with substance exposure and executive functioning, highlighting the importance of identifying this relationship if researchers are to: (a) understand the potential effects that teratogens have on the development of EF, and (b) design effective measures of EF that appropriately tap into potential EF deficits related to substance exposure. Finally, this review discussed a standardized battery of cognitive assessment tools currently in use by researchers across the United States as part of the ABCD Study (i.e., the NIHTB-CB). Prenatal substance exposure may have wide-ranging, harmful effects on both EF development and academic outcomes. For this reason, it is essential that this area of research continues to be explored if we have any hope of developing effective maternal prenatal interventions and/or postnatal programs to identify and remediate exposed children. There is still much to be understood and examined in this important domain.

1.5. The Present Study

Given the lack of research examining low-to-moderate prenatal substance exposure, the current study explored the association between low-to-moderate prenatal alcohol/tobacco exposure and adolescents' subsequent EF and academic performance at two separate time points in their development. Specifically, the study examined whether prenatal teratogen exposure (i.e., maternal-reported low-to-moderate alcohol and/or tobacco use) was associated with negative effects on adolescents' performance on various EF tasks (using the NIHTB-CB) and/or their average grades in school. Furthermore, given that EF has not been consistently defined within the psychological literature, with the field of developmental psychology defining EF more broadly (i.e., cognitive flexibility, working memory, and inhibitory control) and cognitive psychology researchers defining EF more narrowly (i.e., viewing WM as a higher-level, superordinate construct that is separate from EF), this study explored these competing perspectives by examining EF from both perspectives (EF-Broad and EF-Narrow). Additionally, the study used a longitudinal approach to explore the role of *timing* in any such

associations, analyzing data from two separate collection periods: baseline and 2-year follow-up. The dataset used in this study was acquired from the ABCD Study (ABCD, 2021).

As discussed previously, the rationale for focusing on adolescents in this study is three-fold. First, prior research has demonstrated that there are potentially long-term effects of prenatal substance use related to EF development; this is particularly concerning because EFs are significant predictors of a variety of life outcomes (e.g., school readiness, math and reading scores, physical and mental health, professional success, marital harmony, and public safety) (Diamond, 2013; Zelazo & Carlson, 2012; Zelazo & Carlson, 2020). Second, as development unfolds, children are exposed to more challenging cognitive tasks, with children prenatally exposed to substances exhibiting behavioral and cognitive deficits in adolescence that did not appear in early childhood (Olson et al., 1997). Lastly, given that the ABCD Study is following children from ages 9 years through young adulthood, this very large, longitudinal dataset provides a unique opportunity to examine the development of cognitive outcomes in adolescents.

In addition to collecting cognitive performance data using the NIHTB-CB, the ABCD Study also collected data from parents outlining their child's developmental history, including any prenatal exposure to various teratogenic substances (e.g., alcohol, tobacco, illicit drugs, prescription medications). The current study used the following predictor variables based on the level of maternal substance use during pregnancy: (a) low-to-moderate alcohol use (i.e., >0 to 8 drinks on average per week; Skogerbø et al., 2012; Underbjerg et al., 2012), (b) low-to-moderate tobacco use (i.e., >0 to 10 cigarettes per day; Kataoka et al., 2018), and (c) the combination of alcohol and tobacco use. The outcome variables used to assess these types of substance exposure were EF performance (EF-Broad and EF-Narrow; described in detail in the Results section) on the NIHTB-CB (at two separate time points: baseline and 2-year follow-up collection periods) and academic performance (i.e., parent-reported

average grades). The analyses also controlled for demographic and socioeconomic factors, including parent's income, education, and marital status.

With more than 10% of pregnant women reporting having at least one alcoholic beverage in the past 30 days (CDC, 2020), and over 7% of expectant mothers continuing to smoke throughout their pregnancy (CDC, 2018), the importance and timing of this research cannot be overstated. Early atypical EF development can cause a cascade of events that influence future outcomes, so differences observed between children's performances at one age may not be the same as differences observed at the next age (Moore, 2001; Oakes & Rakison, 2019). Specifically, teratogen exposure (even low-to-moderate levels of exposure) may have longer-term developmental effects, even if relatively few differences are observed in infancy or in very early childhood; because more complex cognitive requirements emerge throughout development, early differences may lead to increasingly divergent outcomes later in development in a variety of ways.

2. Method

2.1. ABCD Design and Sample

Using longitudinal data obtained from the ABCD Study, participants included 2,079 children from the following data collection periods: (a) 8.9 to 11.0 years of age (M = 9.94, SD = 0.62; 48.73% female) from the baseline collection period released in 2019, and (b) 10.6 to 13.8 years of age (M = 11.95, SD = 0.65) from the 2-year follow-up collection period released in 2021 (ABCD, 2021; Barch et al., 2021). Information was also obtained from the children's parents or guardians. The ABCD Study includes researchers from 21 research sites around the United States who are currently tracking biological and behavioral development from pre-adolescence (9 years of age) to young adulthood (20 years of age) using standardized assessments of neurocognition, physical/mental health, social/emotional functions, culture/environment, and brain imaging/biospecimen collection for genetic and epigenetic analyses. Curated data from the ABCD Study are released on an annual basis through the NIMH Data Archive.

Data collection and release will continue for 10 years until participants have reached 19-20 years of age. The sample included participants identifying as 72.7% White, 9.5% Black, 0.9% Asian, 16.3% identifying with more than one race/other races, and 0.6% not reporting their race, with 14.7% identifying as Hispanic/Latinx. Table 2 below illustrates the sociodemographic characteristics of the children and parents/guardians included in the present study. ABCD Study information can obtained at http://abcdstudy.org.

Table 2

Sociodemographic Characteristics of ABCD Study Participants at Baseline and 2-Year Follow-up

	Baseline		2-year follow-up	
	n	%	*n*	%
Sex				
Female	1013	48.7	1013	48.7
Male*	1066	51.3	1066	51.3
Parent marital status				
Married	1427	68.6	1422	68.4
Not married*	644	31.0	651	31.3
Not reported	8	0.4	6	0.3
Highest parental education				
< HS diploma*	95	4.6	86	4.1
HS diploma/GED	173	8.3	193	9.3
Some college	641	30.8	638	30.7
Bachelor	587	28.2	563	27.1
Post-graduate degree	582	28.0	598	28.8
Not reported	1	0.0	1	0.0
Household income				
< 50K*	490	23.5	415	20.0
≧ 50K & < 100K	571	27.5	516	24.8
≧ 100K	891	42.9	1023	49.2
Not reported	127	6.1	125	6.0

Note. *n* = 2,079 for each demographic category.
*Indicates the dummy coding reference group for each variable.

2.2. Measures

The neurocognitive measures used in the current analyses included the following tasks from the NIHTB-CB: EF/attention (i.e., Dimensional Change Card Sort and Flanker Inhibitory Control and Attention Task), working memory (i.e., List Sorting Working Memory Test), processing speed (i.e., Pattern

Comparison Processing Speed Test), and episodic memory tasks (i.e., Picture Sequence Memory Test). Each of these five tasks are associated with the measurement of EF-related skills and are included in the analyses as EF composites (EF-Broad and EF-Narrow; see the Results section for a detailed description of the processes used to create these composites). Along with these five EF-related tasks, the NIHTB-CB also includes two tasks designed to measure language (i.e., Picture Vocabulary Test, Oral Reading Recognition Test). Because the current study was focused on EF performance, these two language tasks were not included in the path analyses; however, they were included in the factor analyses described in the Results section.

In addition to the neurocognitive measures listed above, academic performance was measured using parent-provided average grades. Prenatal teratogen exposure was evaluated using information contained in the parent-reported Developmental History Questionnaire. And finally, demographic information about the adolescents and their parents/guardians was obtained from the Demographics Survey.

2.2.1. NIH Toolbox-Cognition Battery

The NIHTB-CB tasks used in these analyses were designed to assess attention, EF, WM, processing speed, and episodic memory, by age group (HealthMeasures, 2021). Tasks used in the baseline and 2-year follow-up collection periods were intended for children aged 7-17 years. Each task yielded a raw score, an uncorrected standard score, and an age-corrected standard score (Casaletto et al., 2015; Thompson et al., 2019). Like the analyses conducted by Thompson et al. (2019), the current analyses used the uncorrected standard scores for each task. Participants completed tasks on an iPad, with total administration time around 35 minutes. Although English and Spanish versions of the tasks exist, all tasks in the ABCD Study used the English versions, as English proficiency was a requirement for the adolescents (not the parents/guardians) to participate in the Study (Luciana et al., 2018).

Flanker Inhibitory Control and Attention Task (FICA). Derived from the Eriksen Flanker task and the Attention Network Task (Luciana et al., 2018; Thompson et al., 2019), FICA measures both inhibitory control and attention, with 20 trials taking 3 minutes to complete (HealthMeasures, 2021; NIH & Northwestern University, 2021). FICA requires participants to pay attention to the middle arrow in a group of five arrows on a touchscreen. At the bottom of the screen, one arrow is pointing left, and one is pointing right. In each trial, participants must press one of the two arrows on the bottom of the touchscreen that represents the direction of the middle arrow (in the 5-arrow sequence). Throughout trials, arrows surrounding the middle arrow may be congruent and/or incongruent with the middle arrow. This requires the participant to stay focused on the direction of the middle arrow and avoid being distracted by the direction of the other arrows. Scoring is based on a 2-vector system using the combination of reaction time and accuracy, with each of the "vectors" ranges falling between 0 and 5, and a combined score ranging from 0 to 10. The accuracy score is given priority over reaction time, meaning that if accuracy levels are less than or equal to 80%, the final computed score will be equal to the accuracy score alone. However, if accuracy levels are above 80%, the final combined score will be the combination of reaction time and accuracy (NIH & Northwestern University, 2021).

List Sorting Working Memory Test (LSWM). Adapted from a letter-number sequencing task developed by Gold et al. (1997), LSWM uses pictures instead of numbers and letters (Luciana et al., 2018). The task involves rapid recall and ordering of different stimuli that are presented orally and verbally. Taking 7 minutes to complete, participants are first shown pictures of different foods and animals (both audio recording and written text). After presentation of the stimuli, participants are asked to state the items back in order by size from the smallest to the largest item on the list. In a 1-category trial, participants list items from one of the categories (animals *or* foods, called 1-list). In a 2-category trial, participants are asked to list foods, then animals, in order from smallest to largest within each category (i.e., foods *and* animals, called 2-list). Trials become increasingly difficult, reaching a maximum

number of 7 items to recall in both the 1-category and 2-category trials (HealthMeasures, 2021; Luciana et al., 2018; NIH & Northwestern University, 2021). Scoring involves adding the total number of items accurately recalled and ordered on the 1-list and 2-list groups, with scores ranging from 0 to 26. Final scores are converted to a nationally normed standard score (NIH & Northwestern University, 2021).

Dimensional Change Card Sort (DCCS). Adapted from the Dimensional Change Card Sort (DCCS) task developed by Zelazo (2006), DCCS measures EF and cognitive flexibility, focusing on assessing the participant's cognitive capacity to organize, plan, and monitor their behaviors in a goal-oriented way (HealthMeasures, 2021). Taking 4 minutes to complete, participants must focus on two objects (e.g., brown boat and white rabbit) at the bottom of a touchscreen. In each trial, a third object is shown at the top of the screen that is the same shape or color as the original two objects. Trials are divided into color game trials and shape game trials. In color game trials, participants must touch the object (i.e., boat or rabbit) that matches the *color* of the third object. In contrast, in shape game trials, participants must touch the object that matches the *shape* of the third object. Additionally, "switch" trials are used, whereby participants must change the dimension being matched. For example, following four consecutive trials matching the object's *shape*, the participant may be asked to match the object's *color* on the next trial and then go back to matching based on *shape*, requiring the cognitive flexibility to rapidly choose the correct stimulus (HealthMeasures, 2021; Luciana et al., 2018). Based on reaction time and accuracy, DCCS uses the same scoring method as FICA (NIH & Northwestern University, 2021).

Pattern Comparison Processing Speed Test (PCPS). Derived from the Salthouse et al. (1991) Pattern Comparison Task, PCPS was designed to measure visual processing speed. The task takes 3 minutes to complete, requiring participants to determine if two pictures, shown side-by-side, are identical or not. Participants are asked to assess the identicalness of as many picture pairs as possible in a specified period of time (HealthMeasures, 2021; Luciana et al., 2018; NIH & Northwestern University, 2021). Raw scores are the number of items accurately answered in 90 seconds of response time, with

scores ranging from 0 to 130. Final scores are converted to normative standard scores (NIH & Northwestern University, 2021).

Picture Sequence Memory Test (PSMT). Designed to measure episodic memory, PSMT assesses the cognitive processes that require acquisition, storage, and retrieval of novel information (HealthMeasures, 2021). Taking 7 minutes to complete, participants are required to arrange a set of picture tiles on a touchscreen in the correct sequence. The tiles represent an activity or event presented in a particular sequence. After viewing the sequence, the tiles are rearranged in a scrambled sequence and participants must move the tiles into empty boxes on a touchscreen in the order in which the event/activity was originally presented. The task contains two separate trials with 6-18 picture tiles and requires accuracy, not speed (HealthMeasures, 2021; Luciana et al., 2018; NIH & Northwestern University, 2021). Using an Item Response Theory (IRT) method, the number of neighboring pairs of tiles for trials 1 and 2 are converted to a theta score that represents the participant's estimated episodic memory ability (NIH & Northwestern University, 2021).

Picture Vocabulary Test (PVT). Derived from the Peabody Picture Vocabulary Test, PVT assesses receptive vocabulary and language (Luciana et al., 2018). Respondents are required to specify which picture, out of four picture options on a touchscreen, best matches the meaning of a specified word. For example, the four picture options may include: (a) cupcake, (b) toy, (c) hamburger, and (d) banana. After four picture blocks appear on the screen, a pre-recorded voice says a word, such as "banana." Respondents are instructed to touch the screen to select the picture that most closely matches the specified word (HealthMeasures, 2021). The test uses computer-adaptive testing (CAT), allowing for adaptations in difficulty level based on the respondent's level of competence, and takes 4 minutes to complete (HealthMeasures, 2021; Luciana et al., 2018). PVT uses IRT, with a theta score calculated for each participant. The present study used the uncorrected standard score. An age-corrected standard

score around 100 indicated average vocabulary ability, with a score of 70 or below indicating low language ability and a score of 130 suggesting superior ability (NIH and Northwestern University, 2021).

Oral Reading Recognition (ORR). Designed to measure reading decoding skills and other cognitive skills associated with reading, this 3-minute task requires participants to read and say words and letters aloud as accurately as possible (HealthMeasures, 2021). Like PSMT and PVT, ORR uses CAT technology, allowing for adaptations in difficulty level, based on the respondent's competence level. Unlike the other tasks, this task requires input from the tester, who must score each word/letter pronunciation as either correct or incorrect (HealthMeasures, 2021; Luciana et al., 2018; NIH and Northwestern University, 2021). Using an IRT method, the resulting theta score represents the participant's overall reading performance/ability (NIH and Northwestern University, 2021).

2.2.2. Average Grades

In the current study, parent-reported average grades were used to assess adolescent academic performance. In the ABCD Study, educational attainment was obtained via school records provided by the parent/guardian. Participants average grades at the baseline and 2-year follow-up collection periods are illustrated in Table 3 below.

Table 3

Participants' Average Grades at Baseline and 2-Year Follow-up

	Baseline		2-year follow-up	
Average grades	*n*	%	*n*	%
A/Excellent	983	47.3	1031	49.6
B/Good	692	33.3	724	34.8
C/Average	228	11.0	220	10.6
D/Below average	28	1.3	51	2.4
F/Struggling a lot	10	0.5	8	0.4
Ungraded/not reported	138	6.6	45	2.2

Note. *n* = 2,079.

2.2.3. Developmental History Questionnaire

The Developmental History Questionnaire has its origins in the National Comorbidity Survey, Adolescent Component, with additional questions included to address maternal substance use throughout pregnancy (Barch et al., 2018). The survey looked at prenatal exposure and exposure during early development, including (a) maternal use of medications, drugs, alcohol, and tobacco, (b) prenatal care, (c) maternal health conditions, (d) premature delivery, (e) any complications during birth, and (f) developmental milestones (Barch et al., 2018). Parents or guardians completed the 15-minute assessment only during the baseline data collection period (ABCD, 2021).

The variables used in the current study were adapted from parent/guardian responses to questions about maternal substance use before knowing of pregnancy, specifically alcohol and tobacco use. The variables included scores based on the level of maternal substance use during pregnancy, as follows: (a) low-to-moderate alcohol use (i.e., >0 to 8 drinks on average per week; Skogerbø et al., 2012; Underbjerg et al., 2012), (b) low-to-moderate tobacco use (i.e., >0 to 10 cigarettes per day; Kataoka et al., 2018), and (c) the combination of alcohol and tobacco use. The tobacco use only and alcohol use only variables were reported as quantities (i.e., tobacco use was reported as the number of cigarettes smoked per day; alcohol use was reported as the average number of drinks consumed per week). In contrast, the combined use variable (i.e., use of both alcohol AND tobacco during pregnancy) was a dummy coded variable (0 = no combined use, 1 = combined use), whereby only parents who reported maternal use of both substances during pregnancy were coded as 1 (i.e., combined use). To be included in the overall study, only adolescents who were exposed to prenatal alcohol and/or tobacco exposure were included in the analyses. Maternal substance use before knowing of pregnancy are illustrated in Table 4 below.

Table 4

Maternal Prenatal Substance Use Before Knowing of Pregnancy

	Before knowing of pregnancy				
Substance use	*n*	%	*M*	*SD*	*Max*

Tobacco use	843	40.5	3.46	5.73	50
Alcohol use	1564	75.2	3.31	4.10	52
Combined use*	356	17.1			

Note. *n* = 2,079. Tobacco use = parent-reported cigarettes per day. Alcohol use = parent- reported average number of drinks per week.
*Combined use = parent-reported use of both alcohol AND tobacco during pregnancy (dummy coded variable).

2.2.4. Demographics Survey

The demographics survey was modified from the PhenX Toolkit (Barch et al., 2018), which contains consensus measures for *Phen*otypes and e*X*posures. PhenX was funded by the National Institutes of Health (NIH) Genomic Resource Grant and was designed to standardize data collection protocols used in biomedical research (PhenX Toolkit, 2020). Parents or guardians completed the 5-minute survey, which included key demographic variables, gender, race, socioeconomic status (SES), family structure, occupation, and education (ABCD, 2021). The demographic variables controlled for in the present study included parent's income, education, and marital status.

2.3. Statistical Approach

Given the longitudinal nature of this study, the statistical analyses were designed to examine outcomes at two time points (i.e., baseline and 2-year follow-up collection periods), specifically looking at the relationships between prenatal substance exposure and EF task performance on the NIHTB-CB and academic achievement (i.e., parent-reported average grades). As mentioned earlier, EF is defined differently depending on the specific area of psychology referring to this construct. Researchers in the field of developmental psychology typically measure EF behaviorally as (a) cognitive flexibility, (b) working memory, and (c) inhibitory control (Diamond, 2013; Zelazo, 2015). In contrast, cognitive psychology researchers examining individual differences typically define EF more narrowly and view WM as a higher-level, superordinate construct that is separate from EF (Conway & Engle, 1994; Conway et al., 2021). To explore these competing perspectives, this paper examined EF from both of these points of view: (a) a broad definition of EF (EF-Broad; using the definition used in developmental psychology

research) and (b) a narrow definition of EF (EF-Narrow; using the definition used in cognitive psychology individual differences research). The NIHTB-CB tasks relevant to the broad definition of EF include: DCCS, FICA, LSWM, PCPS, and PSMT (Bauer & Zelazo, 2013; Moore & Conway, under review). The NIHTB-CB tasks relevant to the narrow definition of EF include: DCCS, FICA, and PCPS (Bauer & Zelazo, 2013; Moore & Conway, under review).

2.3.1. The Prediction

The prediction was that when EF is broadly defined, adolescents who were prenatally exposed to alcohol and/or tobacco will exhibit stronger effects (i.e., a greater reduction in performance on EF tasks and average grades) than when EF is narrowly defined. If this prediction holds true, then any reduced performance when EF is broadly defined would mean that differences between the analyses are due to the relationship between WM and teratogen exposure.

The rationale behind this prediction is rooted in the relationship between the brain areas believed to be responsible for the various aspects of EF and the brain areas affected by prenatal substance exposure. For instance, a narrow definition of EF that does not include tasks measuring WM requires only goal maintenance and no memory load. This type of EF (narrowly defined) is associated with the prefrontal parietal network of the brain (Bor & Seth, 2012). In contrast, a broad definition of EF that includes WM tasks introduces memory load. Memory load requires more than just goal maintenance; it also requires the ability to remember an increasing number of items. By introducing memory load, additional areas of the brain are recruited into action [e.g., the medial temporal lobe and the hippocampus (Axmacher et al., 2007; Raslau et al., 2015)], and these regions of the brain (like every other area of the brain) are expected to be impacted by prenatal substance exposure (Huizink & Mulder, 2006; Julvez et al., 2007; Ross et al., 2015; Uban et al., 2020). Therefore, a broadly defined measure of EF that requires activity in additional brain areas means that there are more cognitive mechanisms in use when compared to a narrower definition of EF.

In general, any teratogenic substance introduced by the mother during pregnancy may interfere with the normal, healthy development of the fetal brain and the associated cognitive processes. Consequently, when children and adolescents prenatally exposed to teratogenic substances are subsequently tested on tasks measuring EF, tasks that examine EF more broadly will naturally tap into more areas of the brain with multiple cognitive mechanisms, potentially revealing broader deficits in executive functioning. Examining EF using a narrow definition alone would only reveal relationships between teratogen exposure and EF in a limited area of the brain. However, expanding the definition to include WM tasks (i.e., a broad EF definition) enables exploration of how teratogen exposure may have affected more areas of the brain, and therefore, more areas of cognition associated with EF skills. Additionally, by examining EF broadly *and* narrowly, this study was able to compare differences between these competing definitions in terms of the extent to which EF (defined in different ways and tapping into more or fewer brain areas) might be affected by prenatal substance exposure.

2.3.2. The Analyses

All analyses were conducted in *R* (Version 4.2.2; 2022-10-31) via *RStudio* (Version 2022.07.2 Build 576) using the *lavaan*, *psych*, and *jmv* packages, and *JASP* (Version JASP 0.16.4). Using ABCD baseline (T1) and 2-year follow-up (T2) data, exploratory factor analyses (EFA) were conducted on the sample dataset (n = 2,079) to determine the latent structure of cognitive abilities. For comparative purposes, EFAs were also conducted on the baseline (T1) and 2-year follow-up (T2) full ABCD dataset (n = 11,876). Following the EFAs, EF-Broad and EF-Narrow were defined by creating composites using scores from each of the relevant NIHTB-CB tasks. Factor scores from the sample dataset EFA were compared via correlation to the EF-Broad and EF-Narrow composites to ensure that the composites would serve as suitable proxies for the factor scores. Additionally, using data from the baseline (T1) and 2-year follow-up (T2) collection periods, path models were used to determine how alcohol exposure,

tobacco exposure, or combined exposure before knowing of pregnancy were associated with EF task performance (EF-Broad and EF-Narrow) and average grades.

Two sets of path analyses were conducted in Study 1 (alcohol use only) and Study 2 (tobacco use only). One set of analyses explored low-to-moderate alcohol use (i.e., alcohol use of >0 to 8 drinks on average per week) or low-to-moderate tobacco use (i.e., tobacco use of >0 to 10 cigarettes per day), using constrained models with datasets exclusively focused on parent-reported prenatal alcohol or tobacco use before knowing of pregnancy. The other set of path analyses examined the full sample dataset (*n* = 2,079), using unconstrained models that included parents/guardians who reported prenatal alcohol or tobacco use above the specified low-to-moderate ranges indicated above.

For Study 3, unlike Studies 1 and 2, combined prenatal alcohol AND tobacco exposure was measured using a dummy coded variable [1 = combined use (use of both alcohol AND tobacco during pregnancy); 0 = no combined use]. For the combined analyses, quantity of use was not taken into consideration (i.e., all parents who reported use of both alcohol AND tobacco during pregnancy were included the analyses). Therefore, only the full sample dataset was examined (*n* = 2,079); low-to-moderate analyses were not possible given the use of a binary variable.

The rationale for conducting path analyses for each of these separate types of substance exposure (alcohol, tobacco, or combined) was based on inconsistent findings reported in prior research. For example, the literature associated with PAE is mixed with some studies reporting cognitive and academic deficits in exposed children (Alati et al., 2013; Jensen et al., 2015; Lees et al., 2020; Mamluk et al., 2017; Olson et al., 1997; Polańska et al., 2015), and other studies reporting improved academic and cognitive performance (Lees et al., 2020; Olson et al., 1997; Todorow et al., 2010; Zuccolo et al., 2013). In contrast, research focused on PTE is less ambiguous, with even low active (i.e., maternal smoking) or passive (i.e., secondhand smoke) exposure associated with neurodevelopmental problems in children, particularly related to poorer academic performance (Banderali et al., 2015; Oh et al., 2021; Polańska et

al., 2015). Lastly, in terms of combined prenatal substance exposure (i.e., use of both alcohol AND tobacco), researchers have reported a synergistic effect, whereby the consequences of the combined exposure are more than the sum of the effects of drinking and smoking independently (Dew et al., 2007; Odendaal et al., 2009; Polańska et al., 2015; Sabra et al., 2018). Given these inconsistent findings across substance types, separate path analyses were warranted.

In each of the path analyses models (for Studies 1, 2, and 3), the EF-Broad and EF-Narrow composite measures served as manifest variables. Models were adjusted for demographic and socioeconomic factors, including parental income, education, and marital status. Descriptions of the each of the path model studies follows.

2.3.1. Study 1: Relationship Between Prenatal Alcohol Use, EF-Broad/EF-Narrow, and Average Grades

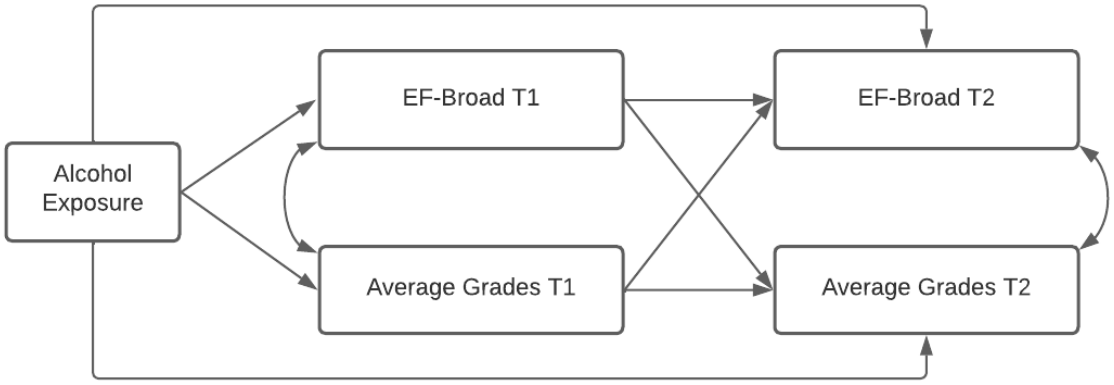
Existing research has suggested that even low-to-moderate PAE may result in reduced performance on cognitive tasks and academic outcomes (Anderson & Choonara, 2007; Jensen et al., 2015; Mamluk et al., 2017; Negrão et al., 2021; Olson et al., 1997; Polańska et al., 2015; Ross et al., 2015; Sithisarn et al., 2012). Additionally, over the course of development children are typically exposed to increasingly challenging cognitive tasks, with children prenatally exposed to substances often exhibiting behavioral and cognitive deficits in adolescence that do not appear in early childhood (Olson et al., 1997). Based on these findings, Study 1 assessed the relationships between PAE and adolescent performance on EF-related tasks (EF-Broad and EF-Narrow) and average grades at two separate time points. Figures 3 and 4 below present a set of hypotheses about the relations between these variables.

For Figures 3 and 4, PAE was hypothesized to be associated with reduced EF task performance (EF-Broad and EF-Narrow) and reduced average grades at both time 1 and time 2, with a greater reduction in EF task performance in the EF-Broad models. Though some previous research on low-to-moderate PAE has yielded positive associations between PAE and EF/academic outcomes, some of those results were weakened after accounting for socioeconomic status and other confounding variables (e.g.,

Zuccolo et al., 2013). Given that the preponderance of research shows varying degrees of deficits and impairments associated with PAE (e.g., Alati et al., 2013; Jensen et al., 2015; Mamluk et al., 2017; Polańska et al., 2015), the present study predicted *reduced* EF task performance and *reduced* average grades. Figures 3 and 4 include one continuous predictor variable (prenatal alcohol use/exposure) and six continuous outcome variables: (a) EF task performance at the baseline collection period (EF-Broad T1 and EF-Narrow T1), (b) EF task performance at the 2-year follow-up collection period (EF-Broad T2 and EF-Narrow T2), (c) average grades T1, and (d) average grades T2. In addition, using the same model structure presented in Figures 3 and 4 below, simple + demographics analyses were also conducted, controlling for demographic variables (i.e., parent income, education, and marital status).

Figure 3

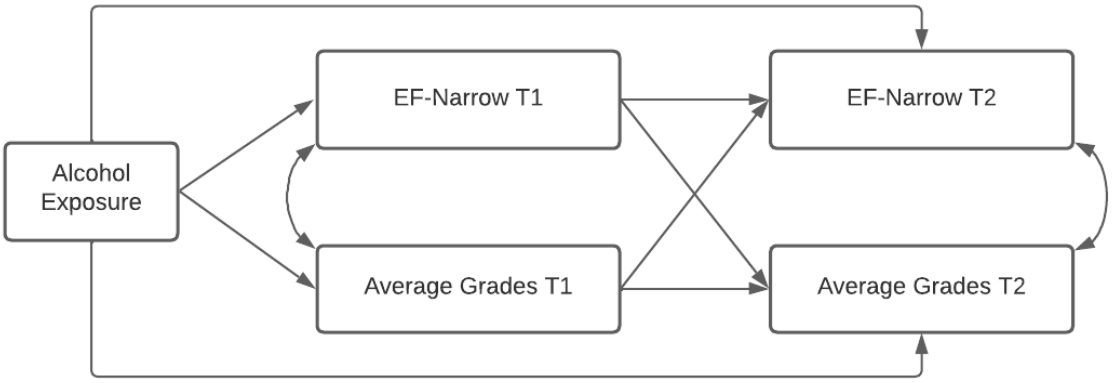
Hypothesized Pathways between Alcohol Use, EF-Broad T1/T2, and Average Grades T1/T2



Note. Alcohol use assessed before knowing of pregnancy. T1 = Baseline collection period. T2 = 2-year follow-up collection period. One-headed, straight arrows indicate a direct relationship between variables. Double-headed, curved arrows indicate a correlation between variables.

Figure 4

Hypothesized Pathways between Alcohol Use, EF-Narrow T1/T2, and Average Grades at T1/T2



Note. Alcohol exposure assessed before knowing of pregnancy. T1 = Baseline collection period. T2 = 2-year follow-up collection period. One-headed, straight arrows indicate a direct relationship between variables. Double-headed, curved arrows indicate a correlation between variables.

2.3.2. Study 2: Relationship Between Prenatal Tobacco Use, EF-Broad/EF-Narrow, and Average Grades

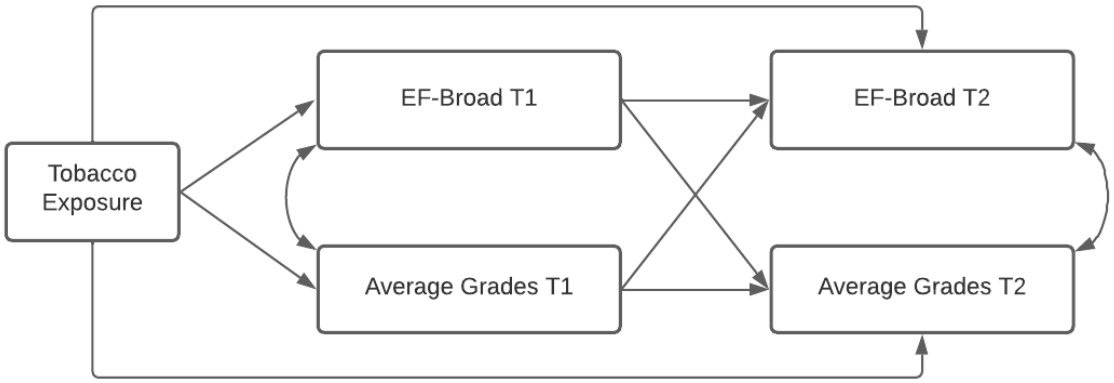
Similar to Study 1, existing research has suggested that even low-to-moderate PTE may result in reduced performance on cognitive tasks and academic outcomes (Agrawal et al., 2010; Banderali et al., 2015; Bennett et al., 2009; Bennett et al., 2013; Cornelius et al., 2007; Cornelius et al., 2011; Drake et al., 2018; Jacobsen et al., 2006; Julvez et al., 2007; Kotimaa et al., 2003; Langley et al., 2007; Lindblad & Hjern, 2010; Polańska et al., 2015; Ross et al., 2015; Sithisarn et al., 2012). Additionally, studies have found relationships between PTE and cognitive functioning, including attention deficits in children at 6 years of age that extended into later adolescence (Bennett et al., 2009; Cornelius et al., 2007; Cornelius et al., 2011; Jacobsen et al., 2006; Kotimaa et al., 2003; Langley et al., 2007; Lindblad & Hjern, 2010), and reduced academic performance and poorer cognitive scores compared to unexposed peers (Agrawal et al., 2010; Bennett et al., 2013; Fried et al., 1992; Fried & Watkinson, 1990). Based on these findings, Study 2 assessed the relationships between PTE and adolescent performance on EF-related tasks (EF-Broad and EF-Narrow) and average grades at two separate time points. Figures 5 and 6 below present a set of hypotheses about the relations between these variables.

For Figures 5 and 6, PTE was hypothesized to be associated with reduced EF task performance (EF-Broad and EF-Narrow) and reduced average grades at both time 1 and time 2, with a greater

reduction in EF task performance in the EF-Broad models. Figures 5 and 6 include one continuous predictor variable (prenatal tobacco use/exposure) and six continuous outcome variables: (a) EF task performance at the baseline collection period (EF-Broad T1 and EF-Narrow T1), (b) EF task performance at the 2-year follow-up collection period (EF-Broad T2 and EF-Narrow T2), (c) average grades T1, and (d) average grades T2. In addition, using the same model structure presented in Figures 5 and 6 below, simple + demographics analyses were also conducted, controlling for demographic variables (i.e., parent income, education, and marital status).

Figure 5

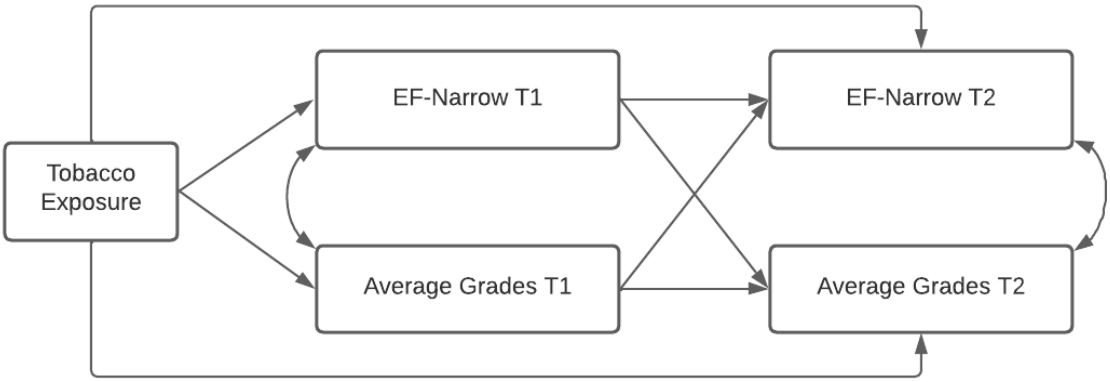
Hypothesized Pathways between Tobacco Use, EF-Broad T1/T2, and Average Grades T1/T2



Note. Tobacco exposure assessed before knowing of pregnancy. T1 = Baseline collection period. T2 = 2-year follow-up collection period. One-headed, straight arrows indicate a direct relationship between variables. Double-headed, curved arrows indicate a correlation between variables.

Figure 6

Hypothesized Pathways between Tobacco Use, EF-Narrow T1/T2, and Average Grades T1/T2



Note. Tobacco exposure assessed before knowing of pregnancy. T1 = Baseline collection period. T2 = 2-year follow-up collection period. One-headed, straight arrows indicate a direct relationship between variables. Double-headed, curved arrows indicate a correlation between variables.

2.3.3. Study 3: Relationship Between Combined Use (Alcohol AND Tobacco), EF-Broad/EF-Narrow, and Average Grades

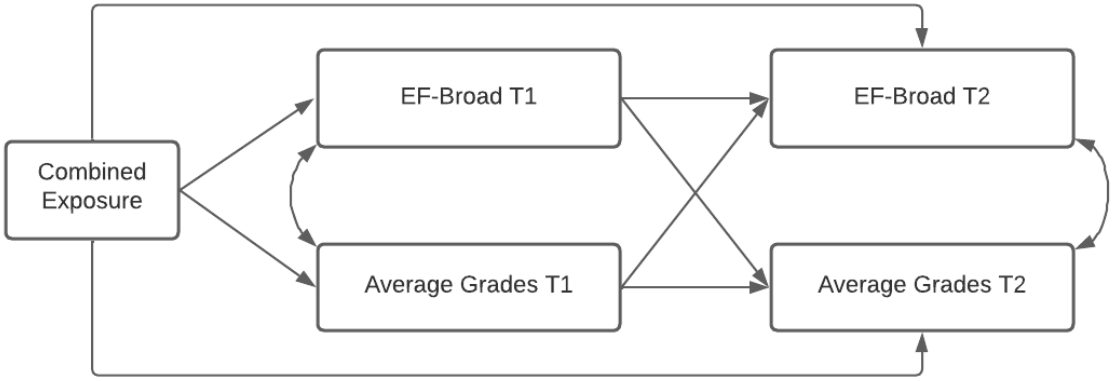
Previous research has suggested that prenatal substance exposure often occurs concurrently, with fetuses exposed to both alcohol and tobacco in utero (Negrão et al., 2021). This type of simultaneous exposure may result in a synergistic effect, whereby the consequences of the combined exposure are more than the sum of the effects of drinking and smoking independently (Dew et al., 2007; Odendaal et al., 2009; Polańska et al., 2015; Sabra et al., 2018). To explore this combined effect (i.e., prenatal exposure to *both* alcohol AND tobacco), Study 3 assessed the relationships between prenatal alcohol AND tobacco exposure and adolescent performance on EF-related tasks (EF-Broad and EF-Narrow) and average grades at two separate time points. Figures 7 and 8 below present a set of hypotheses about the relations between these variables.

For Figures 7 and 8, combined prenatal alcohol AND tobacco exposure was hypothesized to be associated with reduced EF task performance (EF-Broad and EF-Narrow) and reduced average grades at both time 1 and time 2, with a greater reduction in EF task performance in the EF-Broad models. Figures 7 and 8 include one categorical (dummy-coded) predictor variable (combined use/exposure; 0 = no combined use, 1 = combined use) and six continuous outcome variables: (a) EF task performance at the

baseline collection period (EF-Broad T1 and EF-Narrow T1), (b) EF task performance at the 2-year follow-up collection period (EF-Broad T2 and EF-Narrow T2), (c) average grades T1, and (d) average grades T2. In addition, using the same model structure presented in Figures 7 and 8 below, simple + demographics analyses were also conducted, controlling for demographic variables (i.e., parent income, education, and marital status).

Figure 7

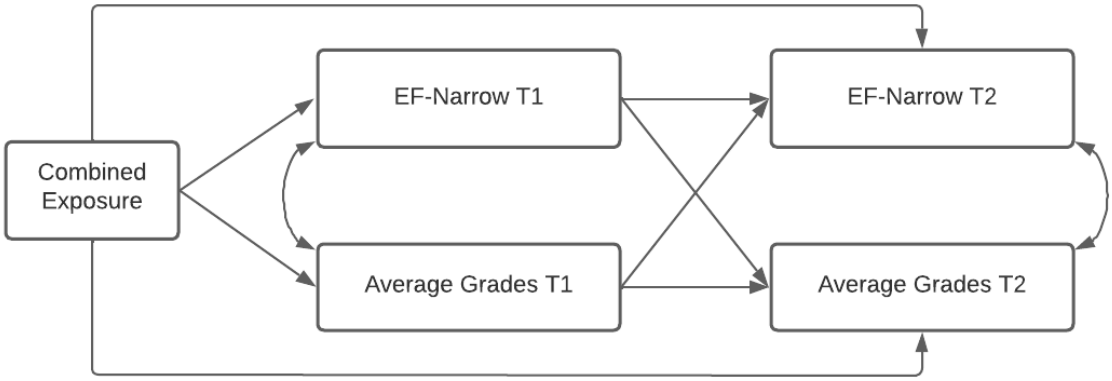
Hypothesized Pathways between Combined Use, EF-Broad T1/T2, and Average Grades T1/ T2



Note. Combined exposure was a dummy coded variable representing alcohol AND tobacco use (0 = no combined use, 1 = combined use). Combined use was assessed before knowing of pregnancy. T1 = Baseline collection period. T2 = 2-year follow-up collection period. One-headed, straight arrows indicate a direct relationship between variables. Double-headed, curved arrows indicate a correlation between variables.

Figure 8

Hypothesized Pathways between Combined Use, EF-Narrow T1/T2, and Average Grades T1/ T2



Note. Combined exposure was a dummy coded variable representing alcohol AND tobacco use (0 = no combined use, 1 = combined use). Combined use was assessed before knowing of pregnancy. T1 = Baseline collection period. T2 = 2-year follow-up collection period. One-headed, straight arrows indicate a direct relationship between variables. Double-headed, curved arrows indicate a correlation between variables.

3. Results

3.1. Description of the Sample Dataset

Prior to data cleaning, the ABCD Study baseline dataset contained over 11,800 children (48% female) (ABCD, 2021). To be included in the current analyses, child participants were required to have completed the NIHTB-CB tasks during the baseline and 2-year follow-up collection periods, as the cognitive tasks were one of two primary outcome variables. After removing participants from the dataset who did not complete the cognitive tasks, the dataset was further examined to remove participants who were not prenatally exposed to alcohol and/or tobacco. Removal of these participants brought the final sample size to 2,079. Sociodemographic characteristics of the participants were presented in the Method section (see Table 2 above). For clarity, Table 5 below presents an outline of each of the analyses conducted in this study.

Table 5

Outline of Analyses

Analysis
1. Examining the Factor Structure of Cognitive Abilities in the NIHTB-CB
Exploratory Factor Analyses: Sample Dataset (n = 2,079)
Sample Dataset Baseline Collection Period (T1)
EFA-Sample-T1
Sample Dataset 2-Year Follow-up Collection Period (T2)
EFA-Sample-T2
Exploratory Factor Analyses: Full ABCD Dataset (n = 11,876)
Full Dataset Baseline Collection Period (T1)
EFA-Full-T1
Full Dataset 2-Year Follow-up Dataset Collection Period (T2)
EFA-Full-T2
2. Defining EF-Broad and EF-Narrow for the Sample Dataset
3. Comparing Factor Scores and EF Composites

4. Comparing EF Composites and Average Grades

5. Path Model Analyses

Low-to-Moderate (Constrained) Path Models

Study 1 (L2M): Relationship Between Prenatal Alcohol Use, EF-Broad/EF-Narrow, and Average Grades

Model 1. L2M Simple: Alcohol Use, EF-Broad, and Average Grades (n = 1,508)

Model 2. L2M Simple + Demographics: Alcohol Use, EF-Broad, and Average Grades (n = 1,508)

Model 3. L2M Simple: Alcohol Use, EF-Narrow, and Average Grades (n = 1,508)

Model 4. L2M Simple + Demographics: Alcohol Use, EF-Narrow, and Average Grades (n = 1,508)

Study 2 (L2M): Relationship Between Prenatal Tobacco Use, EF-Broad/EF-Narrow, and Average Grades

Model 5. L2M Simple: Tobacco Use, EF-Broad, and Average Grades (n = 688)

Model 6. L2M Simple + Demographics: Tobacco Use, EF-Broad, and Average Grades (n = 688)

Model 7. L2M Simple: Tobacco Use, EF-Narrow, and Average Grades (n = 688)

Model 8. L2M Simple + Demographics: Tobacco Use, EF-Narrow, and Average Grades (n = 688)

Full Sample Dataset (Unconstrained) Path Models (n = 2,079)

Study 1: Relationship Between Prenatal Alcohol Use, EF-Broad/EF-Narrow, and Average Grades

Model 9. Simple: Alcohol Use, EF-Broad, and Average Grades

Model 10. Simple + Demographics: Alcohol Use, EF-Broad, and Average Grades

Model 11. Simple: Alcohol Use, EF-Narrow, and Average Grades

Model 12. Simple + Demographics: Alcohol Use, EF-Narrow, and Average Grades

Study 2: Relationship Between Prenatal Tobacco Use, EF-Broad/EF-Narrow, and Average Grades

Model 13. Simple: Tobacco Use, EF-Broad, and Average Grades

Model 14. Simple + Demographics: Tobacco Use, EF-Broad, and Average Grades

Model 15. Simple: Tobacco Use, EF-Narrow, and Average Grades

Model 16. Simple + Demographics: Tobacco Use, EF-Narrow, and Average Grades

Study 3: Relationship Between Combined Use (Alcohol AND Tobacco), EF-Broad/EF-Narrow, and Average Grades

Model 17. Simple: Combined Use, EF-Broad, and Average Grades

Model 18. Simple + Demographics: Combined Use, EF-Broad, and Average Grades

Model 19. Simple: Combined Use, EF-Narrow, and Average Grades

Model 20. Simple + Demographics: Combined Use, EF-Narrow, and Average Grades

3.2. Examining the Factor Structure of Cognitive Abilities in the NIHTB-CB

In the baseline collection period, the ABCD Study tested participants using the full complement of cognitive tasks included in the NIHTB-CB. However, in the 2-year follow-up collection period, the Study dropped two of the tasks from the NIHTB-CB (i.e., list sorting working memory and dimensional change card sort). Given that the list sort task is a measure of WM (and the only measure of WM in the NIHTB-CB), and the DCCS task is a measure of cognitive flexibility and EF, the omission of these two tasks between the baseline and 2-year follow-up collection periods required an examination of the cognitive

tasks to determine how to define EF, broadly and narrowly, in each collection period. To achieve this, two sets of exploratory factor analyses (EFA) were conducted. The first set of EFAs were performed on the sample dataset (*n* = 2,079), and for comparative purposes, the second set of EFAs were performed on the full ABCD dataset (*n* = 11,876). Details of each of these sets of EFAs are described below.

3.2.1. Exploratory Factor Analyses: Sample Dataset (n = 2,079)

Two EFAs were conducted on the sample dataset. The first EFA (EFA-Sample-T1) examined the cognitive tasks included in the baseline collection period, where participants completed all seven cognitive tasks in the NIHTB-CB. The second EFA (EFA-Sample-T2) examined the cognitive tasks included in the 2-year follow-up collection period, where participants only completed five of the seven cognitive tasks in the NIHTB-CB (i.e., participants did not complete the LSWM and DCCS tasks). Even though the verbal tasks contained in the NIHTB-CB (i.e., picture vocabulary and oral reading recognition) were not included in the path analyses (because they are not measures of EF), for the purposes of these EFAs, all available tasks in T1 and T2 were included in the EFAs. By including all of the available tasks in the EFAs, the full structure of the cognitive abilities assessed using the NIHTB-CB could be examined.

Sample Dataset Baseline Collection Period (T1). Descriptive statistics for the seven NIHTB-CB tasks included in the sample dataset baseline collection period are reported in Table 6. A visual inspection of the histograms for each of the tasks revealed normal distributions. Further supporting this conclusion, skew for all cognitive tasks was less than +/- 3.00, and kurtosis was less than +/- 5.00. Correlations between the seven tasks are reported in Table 7.

Table 6

Descriptive Statistics of NIHTB-CB (T1 Sample Dataset)

Tasks	*M*	*SD*	Range	Skew	Kurtosis
PVT	85.88	7.92	59-115	0.31	0.31
FICA	94.97	8.41	53-116	-0.99	1.89
LSWM	97.81	11.48	40-136	-0.51	0.79
DCCS	93.48	9.06	51-120	-0.75	2.33
PCPS	88.75	14.22	42-140	-0.24	-0.00

PSMT	103.49	12.09	76-136	0.21	-0.43
ORR	91.68	6.66	64-118	0.14	1.67

Note. *n* = 2,079. PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; LSWM = List Sort Working Memory; DCCS = Dimensional Change Card Sort; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition.

Table 7

Correlations for NIHTB-CB (T1 Sample Dataset)

Tasks	1	2	3	4	5	6	7
1. PVT	-						
2. FICA	.19	-					
3. LSWM	.40	.26	-				
4. DCCS	.28	.43	.32	-			
5. PCPS	.16	.32	.17	.42	-		
6. PSMT	.25	.15	.30	.26	.15	-	
7. ORR	.53	.22	.39	.27	.15	.22	-

Note. *n* = 2,079. All correlations were significant ($p < .001$). PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; LSWM = List Sort Working Memory; DCCS = Dimensional Change Card Sort; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition.

***EFA-Sample-T1*.** EFA-Sample-T1 was conducted using principal axis factoring extraction and oblique rotation (i.e., direct oblimin). Parallel analysis was used to determine the number of factors. Results of the EFA-Sample-T1 analysis revealed a 3-factor solution (the factor pattern is reported in Table 8, with factor loadings above 0.20): (a) VA, (b) EF, and (c) WM. The factor correlation matrix is reported in Table 9.

Table 8

EFA-Sample-T1 Oblimin Rotated Loadings for 3-Factor Model

Factors/Tasks	Factor loadings			
	1	2	3	Communality
Factor 1: VA				
ORR	**0.77**			0.56
PVT	**0.67**			0.50
LSWM	0.35		0.27	0.37
Factor 2: EF				
DCCS		**0.72**		0.57
PCPS		**0.60**		0.31
FICA		**0.59**		0.34

Factor 3: WM				
PSMT			**0.53**	0.31
Eigenvalue	1.27	1.26	0.45	
Percent of total variance	18%	18%	6%	
Total variance			43%	

Note. *n* = 2,079. VA = Verbal Ability; EF = Executive Function; WM = Working Memory; PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; LSWM = List Sort Working Memory; DCCS = Dimensional Change Card Sort; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition. For each of the NIHTB-CB tasks, uncorrected scores were used in the analyses. Loadings above 0.40 are bolded.

Table 9

EFA-Sample-T1 Correlation Matrix for 3-Factor Model

Factors	1	2	3
1. EF	–		
2. VA	0.47	–	
3. WM	0.49	0.52	–

Note. EF = Executive Function; VA = Verbal Ability; WM = Working Memory.

Sample Dataset 2-Year Follow-up Collection Period (T2). Descriptive statistics for the five NIHTB-CB tasks included in the sample dataset 2-year follow-up collection period are reported in Table 10. A visual inspection of the histograms for each of the tasks revealed normal distributions. Further supporting this conclusion, skew for all cognitive tasks was less than +/- 3.00, and kurtosis was less than +/- 5.00. Correlations between the five tasks are reported in Table 11.

Table 10

Descriptive Statistics of NIHTB-CB (T2 Sample Dataset)

Tasks	*M*	*SD*	Range	Skew	Kurtosis
PVT	89.86	8.24	59-118	0.12	0.27
FICA	100.63	7.29	54-117	-0.91	2.33
PCPS	103.58	14.77	47-153	-0.29	0.55
PSMT	109.54	12.20	76-133	-0.14	-0.41
ORR	95.30	6.39	67-121	0.20	1.57

Note. *n* = 2,079. PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition.

Table 11

Correlations for NIHTB-CB (T2 Sample Dataset)

Tasks	1	2	3	4	5
1. PVT	-				
2. FICA	.26	-			
3. PCPS	.20	.42	-		
4. PSMT	.29	.20	.26	-	
5. ORR	.58	.24	.20	.27	-

Note. *n* = 2,079. All correlations were significant ($p < .001$). PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition.

***EFA-Sample-T2*.** EFA-Sample-T2 was conducted using principal axis factoring extraction and oblique rotation (i.e., direct oblimin). Parallel analysis was used to determine the number of factors. Results of the EFA-Sample-T2 analysis revealed a 2-factor solution (the factor pattern is reported in Table 12, with factor loadings above 0.20): (a) VA and (b) EF. The factor correlation matrix is reported in Table 13.

Table 12

EFA-Sample-T2 Oblimin Rotated Loadings for 2-Factor Model

Factors/Tasks	Factor loadings		
	1	2	Communality
Factor 1: VA			
PVT	**0.80**		0.63
ORR	**0.73**		0.53
PSMT	0.29	0.22	0.18
Factor 2: EF			
PCPS		**0.83**	0.67
FICA		**0.45**	0.29
Eigenvalue	1.32	0.97	
Percent of total variance	26%	19%	
Total variance		46%	

Note. *n* = 2,079. VA = Verbal Ability; EF = Executive Function; PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition. For each of the NIHTB-CB tasks, uncorrected scores were used in the analyses. Loadings above 0.40 are bolded.

Table 13

EFA-Sample-T2 Correlation Matrix for 3-Factor Model

Factors	1	2	3
1. VA	–		
2. EF	0.36	–	

Note. VA = Verbal Ability; EF = Executive Function.

3.2.2. Exploratory Factor Analyses: Full ABCD Dataset (n = 11,876)

For comparative purposes, two additional EFAs were conducted on the full ABCD dataset. Like the EFAs conducted on the sample dataset, the EFAs conducted on the full dataset included: (a) EFA-Full-T1, examining the cognitive tasks included in the baseline collection period, where participants completed all seven cognitive tasks in the NIHTB-CB, and (b) EFA-Full-T2, which examined the cognitive tasks included in the 2-year follow-up collection period, where participants only completed five of the seven cognitive tasks in the NIHTB-CB. Again, even though the verbal tasks contained in the NIHTB-CB (i.e., picture vocabulary and oral reading recognition) were not included in the path analyses (because they are not measures of EF), for the purposes of these additional EFAs, all available tasks in T1 and T2 were included in the EFAs, allowing the full structure of the cognitive abilities assessed using the NIHTB-CB to be examined.

Full Dataset Baseline Collection Period (T1). Descriptive statistics for the seven NIHTB-CB tasks included in the full dataset baseline collection period are reported in Table 14. A visual inspection of the histograms for each of the tasks revealed normal distributions. Further supporting this conclusion, skew for all cognitive tasks was less than +/- 3.00, and kurtosis was less than +/- 5.00. Correlations between the seven tasks are reported in Table 15.

Table 14

Descriptive Statistics of NIHTB-CB (T1 Full Dataset)

Tasks	*M*	*SD*	Range	Skew	Kurtosis
PVT	84.73	8.05	29-119	0.12	0.74
FICA	94.20	8.97	51-116	-1.01	1.61
LSWM	97.03	11.91	36-136	-0.53	0.90
DCCS	92.75	9.37	50-120	-0.82	2.15
PCPS	88.19	14.51	30-140	-0.20	-0.09

PSMT	103.08	12.05	76-136	0.24	-0.40
ORR	91.06	6.86	59-119	0.03	1.61

Note. *n* = 11,876. PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; LSWM = List Sort Working Memory; DCCS = Dimensional Change Card Sort; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition.

Table 15

Correlations for NIHTB-CB (T1 Full Dataset)

Tasks	1	2	3	4	5	6	7
1. PVT	-						
2. FICA	.25	-					
3. LSWM	.40	.29	-				
4. DCCS	.29	.44	.32	-			
5. PCPS	.19	.37	.21	.42	-		
6. PSMT	.24	.20	.34	.27	.19	-	
7. ORR	.53	.27	.40	.29	.19	.23	-

Note. *n* = 11,876. All correlations were significant ($p < .001$). PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; LSWM = List Sort Working Memory; DCCS = Dimensional Change Card Sort; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition.

***EFA-Full-T1*.** EFA-Full-T1 was conducted using principal axis factoring extraction and oblique rotation (i.e., direct oblimin). Parallel analysis was used to determine the number of factors. Similar to the EFA-Sample-T1 analysis, the results of the EFA-Full-T1 analysis also revealed a 3-factor solution (the factor pattern is reported in Table 16, with factor loadings above 0.20): (a) VA, (b) EF, and (c) WM. The factor correlation matrix is reported in Table 17.

Table 16

EFA-Full-T1 Oblimin Rotated Loadings for 3-Factor Model

Factors/Tasks	Factor loadings			
	1	2	3	Communality
Factor 1: VA				
ORR	**0.73**			0.53
PVT	**0.70**			0.53
Factor 2: EF				
PCPS		**0.66**		0.37
DCCS		**0.65**		0.50
FICA		**0.60**		0.39
Factor 3: WM				

PSMT			**0.56**	0.28
LSWM			**0.54**	0.46
Eigenvalue	1.25	1.12	0.68	
Percent of total variance	18%	16%	10%	
Total variance			44%	

Note. *n* = 11,876. VA = Verbal Ability; EF = Executive Function; WM = Working Memory; PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; LSWM = List Sort Working Memory; DCCS = Dimensional Change Card Sort; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition. For each of the NIHTB-CB tasks, uncorrected scores were used in the analyses. Loadings above 0.40 are bolded.

Table 17

EFA-Full-T1 Correlation Matrix for 3-Factor Model

Factors	1	2	3
1. EF	–		
2. VA	0.50	–	
3. WM	0.60	0.69	–

Note. EF = Executive Function; VA = Verbal Ability; WM = Working Memory.

Full Dataset 2-Year Follow-up Dataset Collection Period (T2). Descriptive statistics for the five NIHTB-CB tasks included in the 2-year follow-up full dataset collection period are reported in Table 18. A visual inspection of the histograms for each of the tasks revealed normal distributions. Further supporting this conclusion, skew for all cognitive tasks was less than +/- 3.00, and kurtosis was less than +/- 5.00. Correlations between the five tasks are reported in Table 19.

Table 18

Descriptive Statistics of NIHTB-CB (T2 Full Dataset)

Tasks	*M*	*SD*	Range	Skew	Kurtosis
PVT	88.96	8.49	59-123	0.05	0.19
FICA	100.11	7.65	51-117	-0.98	2.31
PCPS	103.43	15.08	30-163	-0.27	0.48
PSMT	108.43	12.58	76-136	-0.13	-0.45
ORR	94.95	6.72	67-180	0.41	3.80

Note. *n* = 11,876. PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition.

Table 19

Correlations for NIHTB-CB (T2 Full Dataset)

Tasks	1	2	3	4	5
1. PVT	-				
2. FICA	.28	-			
3. PCPS	.21	.42	-		
4. PSMT	.27	.20	.23	-	
5. ORR	.59	.27	.21	.22	-

Note. *n* = 11,876. All correlations were significant ($p < .001$). PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition.

***EFA-Full-T2*.** Like the above EFAs, EFA-Full-T2 was conducted using principal axis factoring extraction and oblique rotation (i.e., direct oblimin). Parallel analysis was used to determine the number of factors. Similar to the EFA-Sample-T2 analysis, the results of the EFA-Sample-T2 analysis also revealed a 2-factor solution (the factor pattern is reported in Table 20, with factor loadings above 0.20): (a) VA and (b) EF. The factor correlation matrix is reported in Table 21.

Table 20

EFA-Full-T2 Oblimin Rotated Loadings for 2-Factor Model

Factors/Tasks	Factor loadings		
	1	2	Communality
Factor 1: VA			
PVT	**0.86**		0.73
ORR	**0.67**		0.48
PSMT	0.24	0.22	0.14
Factor 2: EF			
PCPS		**0.78**	0.60
FICA		**0.49**	0.33
Eigenvalue	1.32	0.95	
Percent of total variance	26%	19%	
Total variance		45%	

Note. *n* = 11,876. VA = Verbal Ability; EF = Executive Function; PVT = Picture Vocabulary Test; FICA = Flanker Inhibitory Control and Attention; PCPS = Pattern Comparison Processing Speed; PSMT = Picture Sequence Memory; ORR = Oral Reading Recognition. For each of the NIHTB-CB tasks, uncorrected scores were used in the analyses. Loadings above 0.40 are bolded.

Table 21

EFA-Full-T2 Correlation Matrix for 3-Factor Model

Factors	1	2	3
1. VA	–		
2. EF	0.38	–	

Note. VA = Verbal Ability; EF = Executive Function.

The findings obtained from the sample dataset EFAs and the full dataset EFAs revealed similar results (with minor variations), confirming that the structure of cognitive abilities in the sample dataset (*n* = 2,079) was consistent with the structure found in the full dataset (*n* = 11,876). This confirmation meant that defining EF-Broad and EF-Narrow in the sample dataset would accurately represent EF-Broad and EF-Narrow in the full dataset.

3.3. Defining EF-Broad and EF-Narrow for the Sample Dataset

As previously stated, one of the objectives of the current study was to examine EF using both a broad (EF-Broad) and a narrow (EF-Narrow) definition. To do this, composite EF measures were created using participant scores from the sample dataset (*n* = 2,079). As stated in the Statistical Approach section above, the NIHTB-CB tasks associated with a broad definition of EF include: DCCS, FICA, LSWM, PCPS, and PSMT (Bauer & Zelazo, 2013; Moore & Conway, under review), and the tasks associated with a narrow definition of EF include: DCCS, FICA, and PCPS (Bauer & Zelazo, 2013; Moore & Conway, under review). Although EF factors were identified via the EFAs presented above, composite measures of EF were created to ensure consistency between the broad and narrow definitions at T1 and T2 (due task inclusion inconsistencies between the T1 and T2 collection periods). To create the composite EF measures, task scores were first standardized (i.e., *z*-scores), and then the relevant tasks were averaged together. These composite EF measures served as manifest variables in the path model analyses described below. The resulting EF-Broad and EF-Narrow composite components for T1 and T2 are presented below in Table 22. Throughout the remainder of this paper, these composites will be referred to as EF-Broad T1, EF-Narrow T1, EF-Broad T2, and EF-Narrow T2.

Table 22

EF-Broad and EF-Narrow Composite Components at T1 and T2

Composites	T1	T2
EF-Broad	PCPS, FICA, DCCS, LSWM, PSMT	PCPS, FICA, PSMT
EF-Narrow	PCPS, FICA, DCCS	PCPS, FICA

Note. *n* = 2,079. PCPS = Pattern Comparison Processing Speed; FICA = Flanker Inhibitory Control and Attention; DCCS = Dimensional Change Card Sort; LSWM = List Sort Working Memory; PSMT = Picture Sequence Memory.

3.4. Comparing Factor Scores and EF Composites

To ensure the EF composites described above would serve as suitable proxies for the EF factor scores identified in the sample dataset EFAs, an examination of the correlation between the factor scores and the composites was performed revealing high correlations between factors and composites (see Table 23).

Table 23

Correlations for Factors Scores and EF Composites

Tasks	1	2	3	4	5	6
1. EF factor	-					
2. WM factor	.71	-				
3. EF-Broad-T1	.94	.85	-			
4. EF-Narrow-T1	.96	.54	.89	-		
5. EF-Broad-T2	.56	.55	.60	.51	-	
6. EF-Narrow-T2	.51	.40	.51	.51	.90	-

Note. *n* = 2,079. All correlations were significant ($p < .001$). EF factor scores and WM factor scores were obtained from the EFA-Sample-T1 analysis. EF-Broad T1 = the broad definition of EF using a composite of NIHTB-CB tasks from the baseline (T1) collection period. EF-Narrow T1 = the narrow definition of EF using a composite of NIHTB-CB tasks from the baseline (T1) collection period. EF-Broad T2 = the broad definition of EF using a composite of NIHTB-CB tasks from the 2-year follow-up (T2) collection period. EF-Narrow T2 = the narrow definition of EF using a composite of NIHTB-CB tasks from the 2-year follow-up (T2) collection period.

3.5. Comparing EF Composites and Average Grades

Based on the results of the correlation analysis above, the EF composites were determined to be suitable proxies for the EF factor scores. Prior to running the path model analyses, correlations between the four EF composites and average grades at T1 and T2 were examined to determine the relationship between each of these outcome variables (see Table 24).

Table 24

Correlations for EF Composites and Average Grades at T1 and T2

Tasks	1	2	3	4	5	6
1. EF-Broad-T1	-					
2. EF-Narrow-T1	.89	-				
3. EF-Broad-T2	.60	.51	-			
4. EF-Narrow-T2	.51	.51	.90	-		
5. Average grades T1	.35	.26	.29	.23	-	
6. Average grades T2	.31	.22	.28	.21	.58	-

Note. *n* = 2,079. EF-Broad T1 = the broad definition of EF using a composite of NIHTB-CB tasks from the baseline (T1) collection period. EF-Narrow T1 = the narrow definition of EF using a composite of NIHTB-CB tasks from the baseline (T1) collection period. EF-Broad T2 = the broad definition of EF using a composite of NIHTB-CB tasks from the 2-year follow-up (T2) collection period. EF-Narrow T2 = the narrow definition of EF using a composite of NIHTB-CB tasks from the 2-year follow-up (T2) collection period. Average grades at T1 and T2 were provided by parents during the baseline and 2-year follow-up collection periods.

The results presented above illustrate strong correlations between the EF composites and average grades. Given these results, the relationships between the EF composites and prenatal substance exposure, and the relationships between average grades and prenatal substance exposure should be similar in the path models presented below.

3.6. Path Model Analyses

Path model analyses were performed to determine how prenatal alcohol exposure, tobacco exposure, or combined exposure were associated with (a) EF task performance (EF-Broad and EF-Narrow) at time 1 and time 2 and (b) average grades at time 1 and time 2. Several sets of path models were used. The first set of path models were constrained to examine low-to-moderate prenatal alcohol exposure or tobacco exposure [with and without controlling for demographic variables (i.e., parental income, education, and marital status)]. Each of these low-to-moderate, constrained path models were based on filtered datasets that included only parents who had reported either (a) alcohol use of >0 to 8 drinks on average per week (Skogerbø et al., 2012; Underbjerg et al., 2012), or (b) tobacco use of >0 to 10 cigarettes per day (Kataoka et al., 2018). For comparative purposes, an additional set of path models were used to examine the full sample dataset (*n* = 2,079) [with and without controlling for demographic

variables (i.e., parental income, education, and marital status)]. Each of these full, unconstrained path models included all the participants in the sample dataset, including parents who had reported alcohol or tobacco use that exceeded the low-to-moderate use parameters described above. Additionally, given that combined substance use (i.e., prenatal alcohol AND tobacco use) was a dummy coded variable (0 = no combined use, 1 = combined use), the combined use analyses were only conducted using the unconstrained, full sample dataset (*n* = 2,079); low-to-moderate analyses were not possible given the use of a binary variable.

The path models presented below are separated by substance use as follows: (a) Study 1 models focused on PAE (low-to-moderate and full sample dataset), (b) Study 2 models focused on PTE (low-to-moderate and full sample dataset), and (c) Study 3 models focused on prenatal combined exposure (full sample dataset only). For both the low-to-moderate, constrained models and the full sample, unconstrained models, EF-Broad and EF-Narrow were examined separately, using the composite measures previously described and serving as manifest variables in the analyses. All path models examined maternal substance use before knowing of pregnancy. For clarity, Table 25 below presents each of the path models used in this study.

Table 25

Low-to-Moderate (Constrained) and Full Sample Dataset (Unconstrained) Path Models

	Study 1	Study 2	Study 3
Path Models	Alcohol use	Tobacco use	Combined use
Low-to-moderate			
EF-Broad	1. Simple	5. Simple	
	2. Simple + demographics	6. Simple + demographics	
EF-Narrow	3. Simple	7. Simple	
	4. Simple + demographics	8. Simple + demographics	
Full sample dataset			
EF-Broad	9. Simple	13. Simple	17. Simple
	10. Simple + demographics	14. Simple + demographics	18. Simple + demographics
EF-Narrow	11. Simple	15. Simple	19. Simple

12. Simple + demographics 16. Simple + demographics 20. Simple + demographics

Note. Low-to-moderate = constrained, focused path models. In low-to-moderate alcohol use models, *n* = 1,508. In low-to-moderate tobacco use models, *n* = 688. Full sample dataset = all participants in the sample regardless of substance use quantity reported (*n* = 2,079). Alcohol use = parent-reported average number of drinks per week. Tobacco use = parent-reported cigarettes per day. Combined use = parent-reported use of both alcohol AND tobacco during pregnancy (dummy coded variable). EF-Broad = the broad definition of EF using a composite of NIHTB-CB tasks. EF-Narrow = the narrow definition of EF using a composite of NIHTB-CB tasks. Simple = path models without controlling for demographic variables. Simple + demographics = path models that controlled for demographic variables (i.e., parental income, education, and marital status).

3.6.1. Low-to-Moderate (Constrained) Path Models

The following path model results are associated with the low-to-moderate (constrained) analyses, meaning parents who reported either (a) alcohol use of >0 to 8 drinks on average per week (Skogerbø et al., 2012; Underbjerg et al., 2012), or (b) tobacco use of >0 to 10 cigarettes per day (Kataoka et al., 2018) were included in the analyses. Study 1 models examined the relationship between low-to-moderate PAE, EF-Broad/EF-Narrow T1/T2, and average grades T1/T2, using simple and simple + demographics models (Models 1-4). Study 2 models explored the relationship between low-to-moderate PTE, EF-Broad/EF-Narrow T1/T2, and average grades T1/T2, using simple and simple + demographics models (Models 5-8). In the results below, low-to-moderate is also referred to as L2M for brevity and to distinguish the low-to-moderate analyses from the full sample dataset analyses.

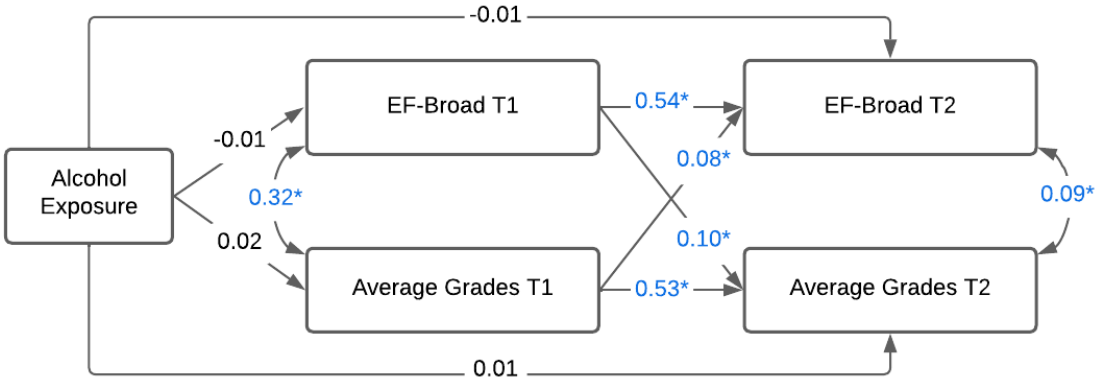
Study 1 (L2M): Relationship Between Prenatal Alcohol Use, EF-Broad/EF-Narrow, and Average Grades

Model 1. L2M Simple: Alcohol Use, EF-Broad, and Average Grades (*n* = 1,508). The results of the low-to-moderate simple path analysis with standardized regression coefficients for alcohol use, EF-Broad, and average grades are presented below in Figure 9. Figure 9 indicates that EF-Broad T1 (β = 0.54, *p* = .000) and average grades T1 (β = 0.08, *p* = .000) were significant positive predictors of EF-Broad T2, with EF-Broad T1 a stronger predictor than average grades T1. EF-Broad T1 (β = 0.10, *p* = .000) and average grades T1 (β = 0.53, *p* = .000) were also significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Broad T1. Average grades T1 (β = 0.32, *p* = .000) was significantly positively correlated with EF-Broad T1, and average grades T2 (β = 0.09, *p* = .002) was

significantly positively correlated with EF-Broad T2, with average grades T1 more strongly correlated with EF-Broad T1 than average grades T2 of EF-Broad T2. However, alcohol exposure before knowing of pregnancy was not a significant predictor of EF-Broad T1/T2 or average grades T1/T2.

Figure 9

Model 1: L2M Simple – Associations Between Alcohol Use, EF-Broad T1/T2, and Average Grades T1/T2



Note. *n* = 1,508. Results of the L2M path analysis for associations between maternal alcohol use before knowing of pregnancy, EF-Broad T1/T2, and average grades T1/T2. Standardized coefficients are presented.
*$p < .05$

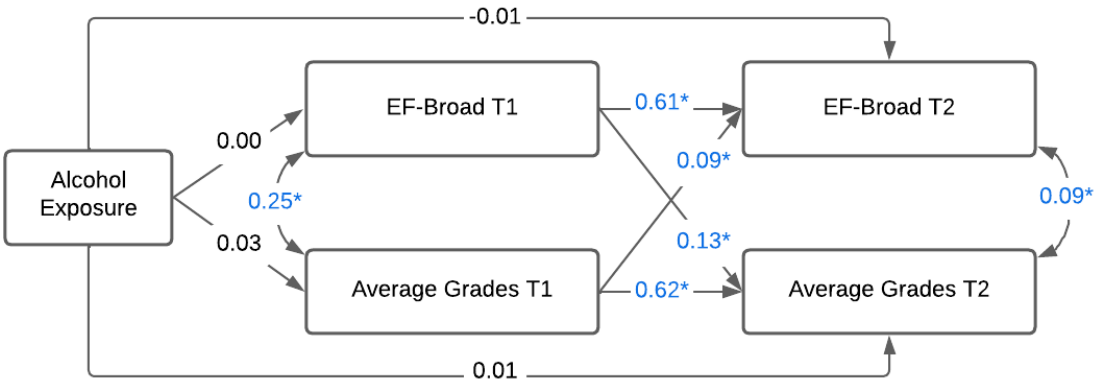
Model 2. L2M Simple + Demographics: Alcohol Use, EF-Broad, and Average Grades (*n* = 1,508).

The results of the low-to-moderate simple + demographics path analysis with standardized regression coefficients for alcohol use, EF-Broad, and average grades, controlling for parental income, education, and marital status, are presented below in Figure 10. Figure 10 indicates that when controlling for demographic variables, EF-Broad T1 (β = 0.61, *p* = .000) and average grades T1 (β = 0.09, *p* = .000) were significant positive predictors of EF-Broad T2, with EF-Broad T1 a stronger predictor than average grades T1. EF-Broad T1 (β = 0.13, *p* = .000) and average grades T1 (β = 0.62, *p* = .000) were significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Broad T1. Average grades T1 (β = 0.25, *p* = .000) was significantly positively correlated with EF-Broad T1, and average

grades T2 (β = 0.09, *p* = .002) was significantly positively correlated with EF-Broad T2; like the simple analysis in Model 1 above, average grades T1 was more strongly correlated with EF-Broad T1 than average grades T2 of EF-Broad T2. However, alcohol exposure before knowing of pregnancy was not a significant predictor of EF-Broad T1/ T2 or average grades T1/T2. Table 26 below presents a summary of the low-to-moderate simple and simple + demographics regression results.

Figure 10

Model 2: L2M Simple + Demographics – Associations Between Alcohol Use, EF-Broad T1/T2, and Average Grades T1/T2



Note. *n* = 1,508. Results of the L2M path analysis for associations between maternal alcohol use before knowing of pregnancy, EF-Broad T1/T2, and average grades T1/T2, controlling for parental income, education, and marital status. Standardized coefficients are presented.
*$p < .05$

Table 26

L2M Models 1 and 2 Standardized Coefficients and Associated Data

	L2M Simple			L2M Simple + Demographics*		
Variable	Standardized estimate	*SE*	*p*-value	Standardized estimate	*SE*	*p*-value
EF-Broad T2 ~						
EF-Broad T1	0.542	0.027	.000	0.612	0.026	.000
Avg grades T1	0.084	0.023	.000	0.094	0.021	.000
Alcohol use	-0.009	0.008	.697	-0.009	0.008	.676

Avg grades T2 ~						
EF-Broad T1	0.102	0.028	.000	0.129	0.026	.000
Avg grades T1	0.532	0.024	.000	0.615	0.021	.000
Alcohol use	0.009	0.008	.696	0.009	0.008	.666
EF-Broad T1 ~						
Alcohol use	-0.009	0.009	.754	0.001	0.008	.966
Married				0.025	0.039	.256
HS diploma/GED				0.119	0.082	.000
Some college				0.261	0.039	.000
Bachelor				0.387	0.035	.000
Post-graduate				0.408	0.035	.000
≧50K & < 100K				0.043	0.036	.048
≧100K				0.118	0.033	.000
Avg grades T1 ~						
Alcohol use	0.022	0.010	.427	0.030	0.010	.144
Married				0.068	0.045	.001
HS diploma/GED				0.142	0.094	.000
Some college				0.298	0.044	.000
Bachelor				0.366	0.040	.000
Post-graduate				0.454	0.040	.000
≧50K & < 100K				0.092	0.042	.000
≧100K				0.144	0.038	.000
EF-Broad T1 ~						
Avg grades T1	0.316	0.013	.000	0.251	0.012	.000
EF-Broad T2 ~						
Avg grades T2	0.087	0.009	.002	0.088	0.009	.002

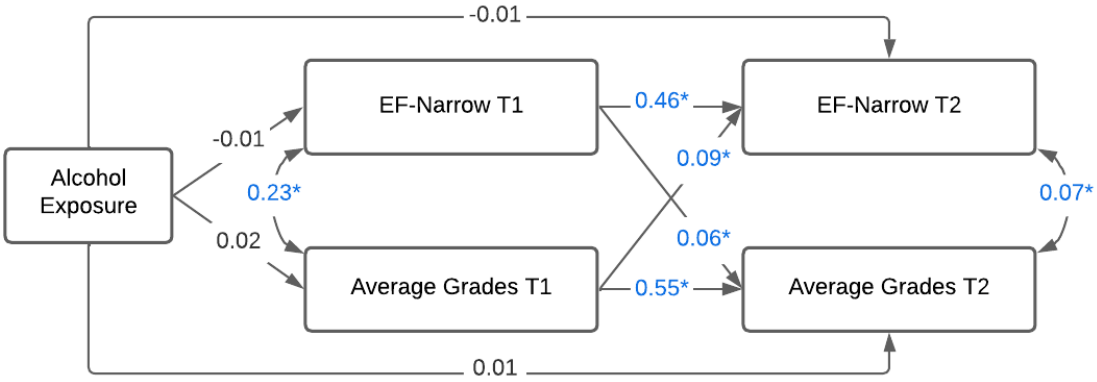
Note. *n* = 1,508. Standardized coefficients are presented.
*Reference groups for dummy coded variables: Parental marital status = Not married; Highest parental education = < HS diploma; Household income = < 50K.

Model 3. L2M Simple: Alcohol Use, EF-Narrow, and Average Grades (*n* = 1,508). The results of the low-to-moderate simple path analysis with standardized regression coefficients for alcohol use, EF-Narrow, and average grades are presented below in Figure 11. Figure 11 indicates that EF-Narrow T1 (β = 0.46, *p* = .000) and average grades T1 (β = 0.09, *p* = .000) were significant positive predictors of EF-Narrow T2, with EF-Narrow T1 a stronger predictor than average grades T1. EF-Narrow T1 (β = 0.06, *p* = .020) and average grades T1 (β = 0.55, *p* = .000) were significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Narrow T1. Average grades T1 (β = 0.23, *p* =

.000) was significantly positively correlated with EF-Narrow T1, and average grades T2 (β = 0.07, *p* = .015) was significantly positively correlated with EF-Narrow T2, with average grades T1 more strongly correlated with EF-Narrow T1 than average grades T2 of EF-Narrow T2. However, alcohol exposure before knowing of pregnancy was not a significant predictor of EF-Narrow T1/T2 or average grades T1/T2.

Figure 11

Model 3: L2M Simple – Associations Between Alcohol Use, EF-Narrow T1/T2, and Average Grades T1/T2



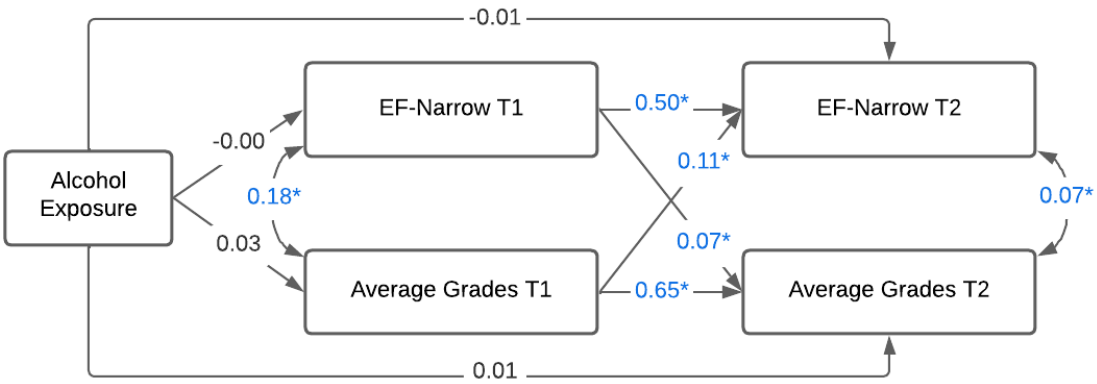
Note. *n* = 1,508. Results of the L2M path analysis for associations between maternal alcohol use before knowing of pregnancy, EF-Narrow T1/T2, and average grades T1/T2. Standardized coefficients are presented.
*$p < .05$

Model 4. L2M Simple + Demographics: Alcohol Use, EF-Narrow, and Average Grades (*n* = 1,508). The results of the low-to-moderate simple + demographics path analysis with standardized regression coefficients for alcohol use, EF-Narrow, and average grades, controlling for parental income, education, and marital status, are presented below in Figure 12. Figure 12 indicates that when controlling for demographic variables, EF-Narrow T1 (β = 0.50, *p* = .000) and average grades T1 (β = 0.11, *p* = .000) were significant positive predictors of EF-Narrow T2, with EF-Narrow T1 a stronger predictor than average grades T1. EF-Narrow T1 (β = 0.07, *p* = .004) and average grades T1 (β = 0.65, *p* = .000)

were significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Narrow T1. Average grades T1 (β = 0.18, *p* = .000) was significantly positively correlated EF-Narrow T1, and average grades T2 (β = 0.07, *p* = .013) was significantly positively correlated EF-Narrow T2; like the simple analysis in Model 3 above, average grades T1 was more strongly correlated with EF-Narrow T1 than average grades T2 of EF-Narrow T2. However, alcohol exposure before knowing of pregnancy was not a significant predictor of EF-Narrow T1/T2 or average grades T1/T2. Table 27 below presents a summary of the low-to-moderate simple and simple + demographics regression results, and Figure 29 in the Appendix presents Models 1 through 4 side-by-side.

Figure 12

Model 4: L2M Simple + Demographics – Associations Between Alcohol Use, EF-Narrow T1/T2, and Average Grades T1/T2



Note. *n* = 1,508. Results of the L2M path analysis for associations between maternal alcohol use before knowing of pregnancy, EF-Narrow T1/T2, and average grades T1/T2, controlling for parental income, education, and marital status. Standardized coefficients are presented.
*$p < .05$

Table 27

L2M Models 3 and 4 Standardized Coefficients and Associated Data

	L2M Simple	L2M Simple + Demographics*

Variable	Standardized estimate	*SE*	*p*-value	Standardized estimate	*SE*	*p*-value
EF-Narrow T2 ~						
EF-Narrow T1	0.461	0.027	.000	0.498	0.026	.000
Avg grades T1	0.093	0.027	.000	0.114	0.023	.000
Alcohol use	-0.005	0.010	.825	-0.009	0.010	.694
Avg grades T2 ~						
EF-Narrow T1	0.055	0.023	.020	0.066	0.023	.004
Avg grades T1	0.552	0.023	.000	0.650	0.020	.000
Alcohol use	0.008	0.008	.726	0.008	0.008	.703
EF-Narrow T1 ~						
Alcohol use	-0.008	0.010	.781	-0.000	0.010	.997
Married				0.023	0.047	.353
HS diploma/GED				0.082	0.099	.001
Some college				0.206	0.047	.000
Bachelor				0.303	0.043	.000
Post-graduate				0.292	0.042	.000
≧50K & < 100K				0.032	0.044	.200
≧100K				0.118	0.040	.000
Avg grades T1 ~						
Alcohol use	0.022	0.010	.427	0.030	0.010	.144
Married				0.068	0.045	.001
HS diploma/GED				0.142	0.094	.000
Some college				0.298	0.044	.000
Bachelor				0.366	0.040	.000
Post-graduate				0.454	0.040	.000
≧50K & < 100K				0.092	0.042	.000
≧100K				0.144	0.038	.000
EF-Narrow T1 ~						
Avg grades T1	0.231	0.015	.000	0.176	0.014	.000
EF-Narrow T2 ~						
Avg grades T2	0.068	0.011	.015	0.071	0.011	.013

Note. *n* = 1,508. Standardized coefficients are presented.
*Reference groups for dummy coded variables: Parental marital status = Not married; Highest parental education = < HS diploma; Household income = < 50K.

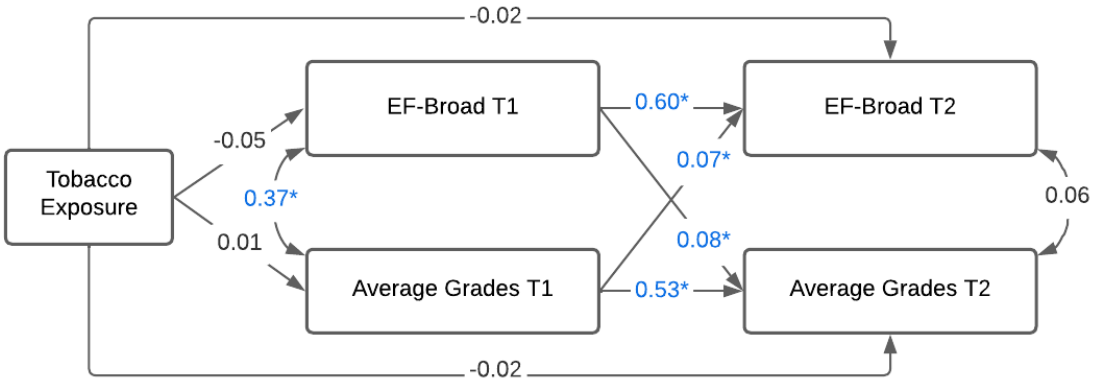
Study 2 (L2M): Relationship Between Prenatal Tobacco Use, EF-Broad/EF-Narrow, and Average Grades

Model 5. L2M Simple: Tobacco Use, EF-Broad, and Average Grades (*n* = 688). The results of the low-to-moderate simple path analysis with standardized regression coefficients for tobacco use, EF-

Broad, and average grades are presented below in Figure 13. Figure 13 indicates that EF-Broad T1 (β = 0.59, *p* = .000) and average grades T1 (β = 0.07, *p* = .047) were significant positive predictors of EF-Broad T2, with EF-Broad T1 a stronger predictor than average grades T1. EF-Broad T1 (β = 0.08 *p* = .018) and average grades T1 (β = 0.53, *p* = .000) were significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Broad T1. Average grades T1 (β = 0.37, *p* = .000) was significantly positively correlated with EF-Broad T1, but average grades T2 (β = 0.06, *p* = .136) was not significantly correlated EF-Broad T2. Tobacco exposure before knowing of pregnancy was not a significant predictor of EF-Broad T1/T2 or average grades T1/T2.

Figure 13

Model 5: L2M Simple – Associations Between Tobacco Use, EF-Broad T1/T2, and Average Grades T1/T2



Note. *n* = 688. Results of the L2M path analysis for associations between maternal tobacco use before knowing of pregnancy, EF-Broad T1/T2, and average grades T1/T2. Standardized coefficients are presented.
*$p < .05$

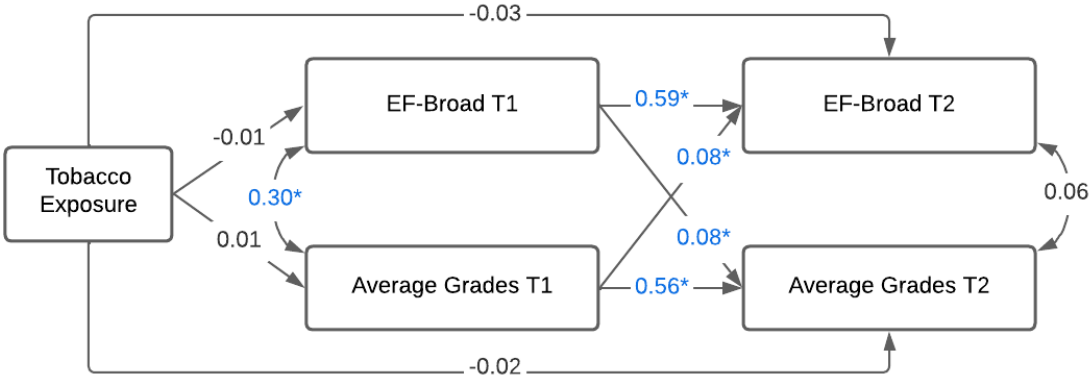
Model 6. L2M Simple + Demographics: Tobacco Use, EF-Broad, and Average Grades (*n* = 688).

The results of the low-to-moderate simple + demographics path analysis with standardized regression coefficients for tobacco use, EF-Broad, and average grades, controlling for parental income, education, and marital status, are presented below in Figure 14. Figure 14 indicates that when controlling for

demographic variables, EF-Broad T1 (β = 0.59, *p* = .000) and average grades T1 (β = 0.08, *p* = .030) were significant positive predictors of EF-Broad T2, with EF-Broad T1 a stronger predictor than average grades T1. EF-Broad T1 (β = 0.08, *p* = .047) and average grades T1 (β = 0.56, *p* = .000) were significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Broad T1. Average grades T1 (β = 0.30, *p* = .000) was significantly positively correlated with EF-Broad T1, but average grades T2 (β = 0.06, *p* = .139) was not significantly correlated with EF-Broad T2. Tobacco exposure before knowing of pregnancy was not a significant predictor of EF-Broad T1/T2 or average grades T1/T2. Table 28 below presents a summary of the low-to-moderate simple and simple + demographics regression results.

Figure 14

Model 6: L2M Simple + Demographics – Associations Between Tobacco Use, EF-Broad T1/T2, and Average Grades T1/T2



Note. *n* = 688. Results of the L2M path analysis for associations between maternal tobacco use before knowing of pregnancy, EF-Broad T1/T2, and average grades T1/T2, controlling for parental income, education, and marital status. Standardized coefficients are presented.
*$p < .05$

Table 28

L2M Models 5 and 6 Standardized Coefficients and Associated Data

	L2M Simple			L2M Simple + Demographics*		
Variable	Standardized estimate	*SE*	*p*-value	Standardized estimate	*SE*	*p*-value
EF-Broad T2 ~						
EF-Broad T1	0.597	0.039	.000	0.587	0.041	.000
Avg grades T1	0.067	0.030	.047	0.080	0.031	.030
Tobacco use	-0.016	0.008	.605	-0.030	0.008	.372
Avg grades T2 ~						
EF-Broad T1	0.084	0.047	.018	0.075	0.049	.047
Avg grades T1	0.534	0.037	.000	0.564	0.037	.000
Tobacco use	-0.019	0.009	.575	-0.015	0.010	.654
EF-Broad T1 ~						
Tobacco use	-0.051	0.009	.208	-0.014	0.009	.709
Married				0.063	0.054	.101
HS diploma/GED				0.079	0.084	.040
Some college				0.189	0.054	.000
Bachelor				0.273	0.068	.000
Post-graduate				0.230	0.083	.000
≧50K & < 100K				0.082	0.057	.032
≧100K				0.082	0.064	.033
Avg grades T1 ~						
Tobacco use	0.006	0.011	.885	0.012	0.011	.753
Married				0.078	0.071	.041
HS diploma/GED				0.088	0.111	.022
Some college				0.269	0.071	.000
Bachelor				0.215	0.090	.000
Post-graduate				0.236	0.110	.000
≧50K & < 100K				0.011	0.075	.779
≧100K				0.049	0.084	.201
EF-Broad T1 ~						
Avg grades T1	0.365	0.025	.000	0.299	0.023	.000
EF-Broad T2 ~						
Avg grades T2	0.060	0.018	.136	0.063	0.019	.139

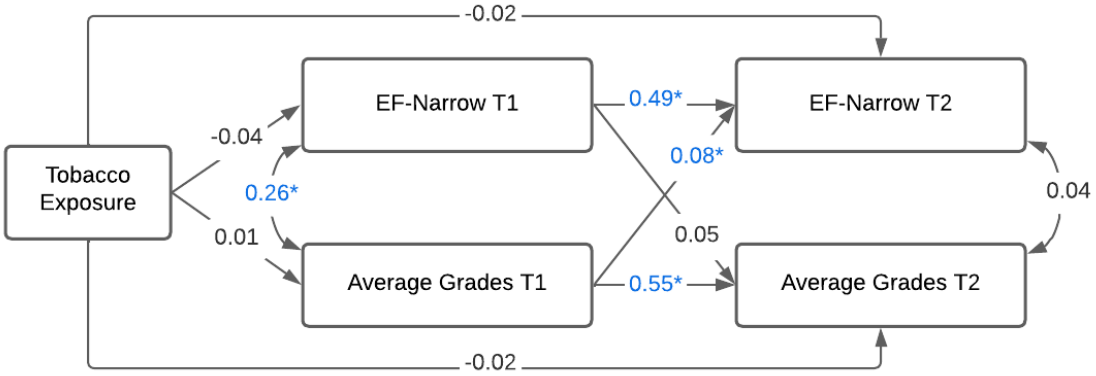
Note. *n* = 688. Standardized coefficients are presented.
*Reference groups for dummy coded variables: Parental marital status = Not married; Highest parental education = < HS diploma; Household income = < 50K.

Model 7. L2M Simple: Tobacco Use, EF-Narrow, and Average Grades (*n* = 688). The results of the low-to-moderate simple path analysis with standardized regression coefficients for tobacco use, EF-Narrow, and average grades are presented below in Figure 15. Figure 15 indicates that EF-Narrow T1 (β

= 0.49, *p* = .000) and average grades T1 (β = 0.08, *p* = .019) were significant positive predictors of EF-Narrow T2, with EF-Narrow T1 a stronger predictor than average grades T1. Average grades T1 (β = 0.55, *p* = .000) was a significant positive predictor of average grades T2. Average grades T1 (β = 0.26, *p* = .000) was significantly positively correlated with EF-Narrow T1. However, tobacco exposure before knowing of pregnancy was not a significant predictor of EF-Narrow T1/T2 or average grades T1/T2.

Figure 15

Model 7: L2M Simple – Associations Between Tobacco Use, EF-Narrow T1/T2, and Average Grades T1/T2



Note. *n* = 688. Results of the L2M path analysis for associations between maternal tobacco use before knowing of pregnancy, EF-Narrow T1/T2, and average grades T1/T2. Standardized coefficients are presented.
*$p < .05$

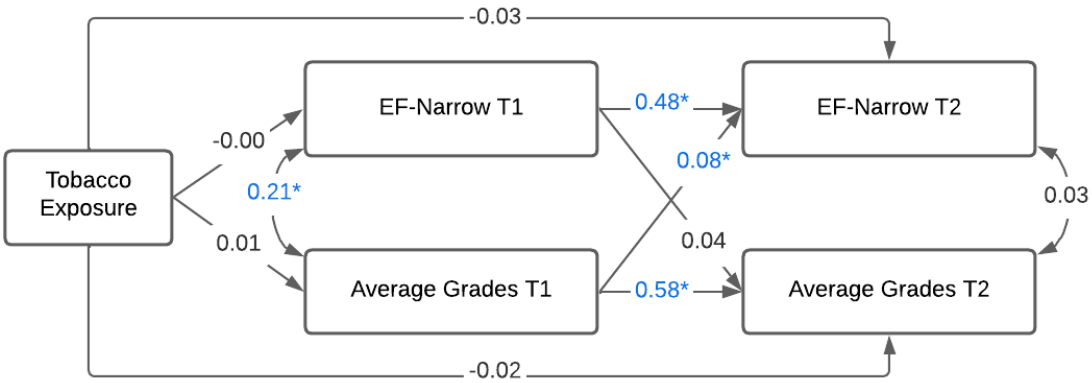
Model 8. L2M Simple + Demographics: Tobacco Use, EF-Narrow, and Average Grades (*n* = 688).

The results of the low-to-moderate simple + demographics path analysis with standardized regression coefficients for tobacco use, EF-Narrow, and average grades, controlling for parental income, education, and marital status, are presented below in Figure 16. Figure 16 indicates that when controlling for demographic variables, EF-Narrow T1 (β = 0.48, *p* = .000) and average grades T1 (β = 0.08, *p* = .049) were significant positive predictors of EF-Narrow T2, with EF-Narrow T1 a stronger predictor than average grades T1. Average grades T1 (β = 0.58, *p* = .000) was a significant positive predictor of average grades

T2. Average grades T1 (β = 0.21, *p* = .000) was significantly positively correlated with EF-Narrow T1. However, tobacco exposure before knowing of pregnancy was not a significant predictor of EF-Narrow T1/T2 or average grades T1/T2. Table 29 below presents a summary of the low-to-moderate simple and simple + demographics regression results, and Figure 30 in the Appendix presents Models 5 through 8 side-by-side.

Figure 16

Model 8: L2M Simple + Demographics – Associations Between Tobacco Use, EF-Narrow T1/T2, and Average Grades T1/T2



Note. *n* = 688. Results of the L2M path analysis for associations between maternal tobacco use before knowing of pregnancy, EF-Narrow T1/T2, and average grades T1/T2, controlling for parental income, education, and marital status. Standardized coefficients are presented.
*$p < .05$

Table 29

L2M Models 7 and 8 Standardized Coefficients and Associated Data

	L2M Simple			L2M Simple + Demographics*		
Variable	Standardized estimate	*SE*	*p*-value	Standardized estimate	*SE*	*p*-value
EF-Narrow T2 ~						
EF-Narrow T1	0.490	0.040	.000	0.476	0.042	.000
Avg grades T1	0.084	0.037	.019	0.076	0.037	.049
Tobacco use	-0.019	0.010	.574	-0.032	0.011	.385

Avg grades T2 ~						
EF-Narrow T1	0.050	0.038	.143	0.041	0.040	.253
Avg grades T1	0.552	0.036	.000	0.582	0.035	.000
Tobacco use	-0.021	0.009	.527	-0.017	0.010	.627
EF-Narrow T1 ~						
Tobacco use	-0.038	0.010	.338	-0.003	0.011	.933
Married				0.045	0.067	.269
HS diploma/GED				0.012	0.104	.770
Some college				0.078	0.067	.056
Bachelor				0.174	0.085	.000
Post-graduate				0.161	0.104	.000
≧50K & < 100K				0.055	0.071	.184
≧100K				0.061	0.079	.137
Avg grades T1 ~						
Tobacco use	0.006	0.011	.885	0.012	0.011	.753
Married				0.078	0.071	.041
HS diploma/GED				0.088	0.111	.022
Some college				0.269	0.071	.000
Bachelor				0.215	0.090	.000
Post-graduate				0.236	0.110	.000
≧50K & < 100K				0.011	0.075	.779
≧100K				0.049	0.084	.201
EF-Narrow T1 ~						
Avg grades T1	0.256	0.029	.000	0.207	0.028	.000
EF-Narrow T2 ~						
Avg grades T2	0.044	0.023	.278	0.034	0.024	.428

Note. *n* = 688. Standardized coefficients are presented.
*Reference groups for dummy coded variables: Parental marital status = Not married; Highest parental education = < HS diploma; Household income = < 50K.

3.6.2. Full Sample Dataset (Unconstrained) Path Models (n = 2,079)

For comparative purposes with the low-to-moderate path model analyses above, the following path model results are associated with the full sample dataset (unconstrained), meaning all parents who reported any quantity of prenatal alcohol and/or tobacco use were included in the analyses (*n* = 2,079). Study 1 models examined the relationship between PAE, EF-Broad/EF-Narrow T1/T2, and average grades T1/T2, using simple and simple + demographics models for the full sample dataset (Models 9-10). Study 2 models explored the relationship between PTE, EF-Broad/EF-Narrow T1/T2, and average grades

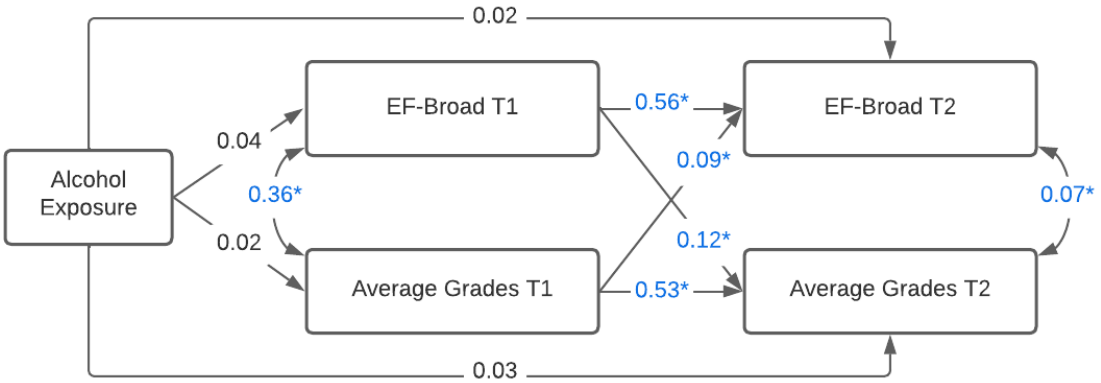
T1/T2, using simple and simple + demographics models using the full sample dataset (Models 13-16). Study 3 models looked at the relationship between prenatal combined alcohol AND tobacco exposure, EF-Broad/EF-Narrow T1/T2, and average grades T1/T2, using simple and simple + demographics models using the full dataset (Models 17-20). As mentioned previously, the combined use models included a dummy coded variable (0 = no combined use, 1 = combined use).

Study 1: Relationship Between Prenatal Alcohol Use, EF-Broad/EF-Narrow, and Average Grades

Model 9. Simple: Alcohol Use, EF-Broad, and Average Grades. The results of the simple path analysis with standardized regression coefficients for alcohol use, EF-Broad, and average grades are presented below in Figure 17. Figure 17 indicates that EF-Broad T1 (β = 0.56, *p* = .000) and average grades T1 (β = 0.09, *p* = .000) were significant positive predictors of EF-Broad T2, with EF-Broad T1 a stronger predictor than average grades T1. EF-Broad T1 (β = 0.12, *p* = .000) and average grades T1 (β = 0.53, *p* = .000) were significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Broad T1. Average grades T1 (β = 0.36, *p* = .000) was significantly positively correlated with EF-Broad T1, and average grades T2 (β = 0.07, *p* = .004) was significantly positively correlated with EF-Broad T2, with average grades T1 more strongly correlated with EF-Broad T1 than average grades T2 of EF-Broad T2. However, alcohol exposure before knowing of pregnancy was not a significant predictor of EF-Broad T1/T2 or average grades T1/T2.

Figure 17

Model 9: Simple – Associations Between Alcohol Use, EF-Broad T1/T2, and Average Grades T1/T2

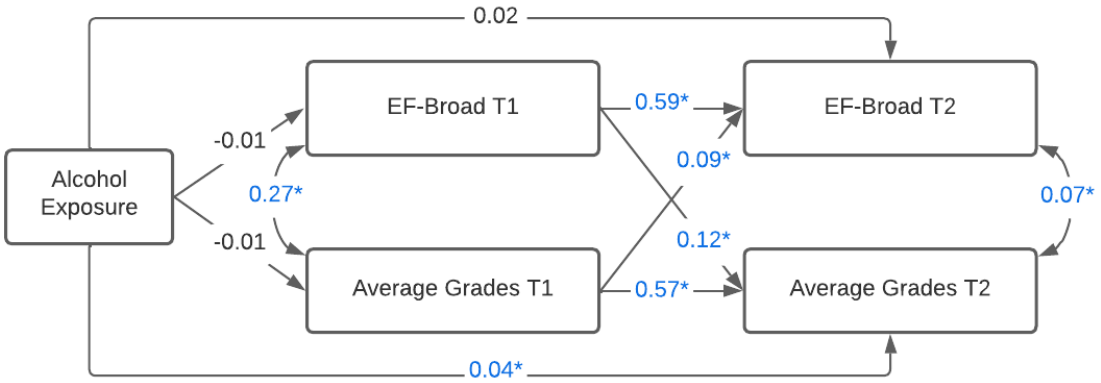


Note. *n* = 2,079. Results of the path analysis for associations between maternal alcohol use before knowing of pregnancy, EF-Broad T1/T2, and average grades T1/T2. Standardized coefficients are presented.
*$p < .05$

Model 10. Simple + Demographics: Alcohol Use, EF-Broad, and Average Grades. The results of the simple + demographics path analysis with standardized regression coefficients for alcohol use, EF-Broad, and average grades, controlling for parental income, education, and marital status, are presented below in Figure 18. Figure 18 indicates that when controlling for demographic variables, EF-Broad T1 (β = 0.59, p = .000) and average grades T1 (β = 0.09, p = .000) were significant positive predictors of EF-Broad T2, with EF-Broad T1 a stronger predictor than average grades T1. EF-Broad T1 (β = 0.12, p = .000), average grades T1 (β = 0.57, p = .000), and alcohol use before knowing of pregnancy (β = 0.04, p = .042) were significant *positive* predictors of average grades T2, with average grades T1 a stronger predictor than either EF-Broad T1 or prenatal alcohol use. Average grades T1 (β = 0.27, p = .000) was significantly positively correlated with EF-Broad T1, and average grades T2 (β = 0.07, p = .003) was significantly positively correlated with EF-Broad T2; like the simple analysis in Model 9 above, average grades T1 was more strongly correlated with EF-Broad T1 than average grades T2 of EF-Broad T2. However, although alcohol exposure before knowing of pregnancy was a significant *positive* predictor of average grades T2; it was not a significant predictor of EF-Broad T1/T2 or average grades T1. Table 30 below presents a summary of the simple and simple + demographics regression results.

Figure 18

Model 10: Simple + Demographics – Associations Between Alcohol Use, EF-Broad T1/T2, and Average Grades T1/T2



Note. *n* = 2,079. Results of the path analysis for associations between maternal alcohol use before knowing of pregnancy, EF-Broad T1/T2, and average grades T1/T2, controlling for parental income, education, and marital status. Standardized coefficients are presented.
*$p < .05$

Table 30

Models 9 and 10 Standardized Coefficients and Associated Data

	Simple			Simple + Demographics*		
Variable	Standardized estimate	*SE*	*p*-value	Standardized estimate	*SE*	*p*-value
EF-Broad T2 ~						
EF-Broad T1	0.564	0.02	.000	0.588	0.023	.000
Avg grades T1	0.093	0.02	.000	0.093	0.018	.000
Alcohol use	0.022	0.00	.233	0.020	0.003	.277
Avg grades T2 ~						
EF-Broad T1	0.115	0.03	.000	0.124	0.025	.000
Avg grades T1	0.532	0.02	.000	0.565	0.020	.000
Alcohol use	0.033	0.00	.084	0.038	0.004	.042
EF-Broad T1 ~						
Alcohol use	0.041	0.00	.078	-0.007	0.003	.740
Married				0.037	0.032	.075
HS diploma/GED				0.076	0.056	.000
Some college				0.199	0.031	.000

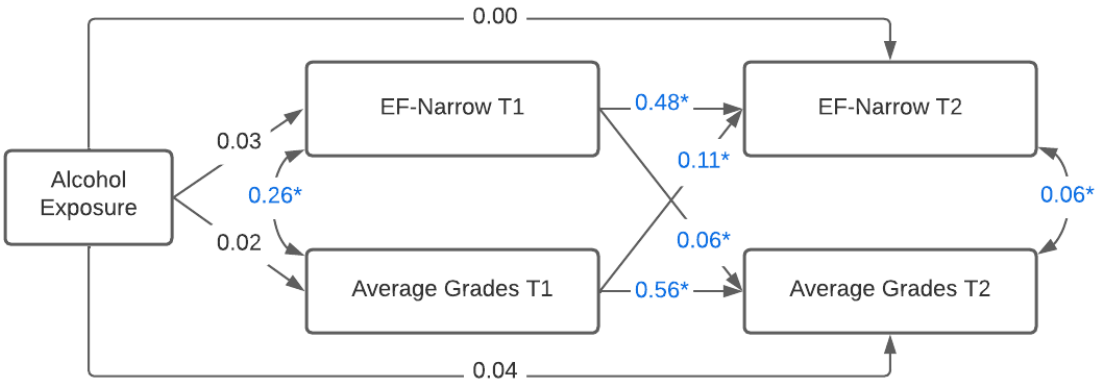
Bachelor				0.307	0.031	.000
Post-graduate				0.320	0.032	.000
≧50K & < 100K				0.079	0.031	.000
≧100K				0.148	0.029	.000
Avg grades T1 ~						
Alcohol use	0.023	0.00	.329	-0.007	0.004	.741
Married				0.054	0.039	.007
HS diploma/GED				0.084	0.069	.000
Some college				0.229	0.038	.000
Bachelor				0.285	0.038	.000
Post-graduate				0.362	0.038	.000
≧50K & < 100K				0.070	0.038	.001
≧100K				0.142	0.035	.000
EF-Broad T1 ~						
Avg grades T1	0.355	0.01	.000	0.270	0.011	.000
EF-Broad T2 ~						
Avg grades T2	0.068	0.01	.004	0.071	0.009	.003

Note. *n* = 2,079. Standardized coefficients are presented.
*Reference groups for dummy coded variables: Parental marital status = Not married; Highest parental education = < HS diploma; Household income = < 50K.

Model 11. Simple: Alcohol Use, EF-Narrow, and Average Grades. The results of the simple path analysis with standardized regression coefficients for alcohol use, EF-Narrow, and average grades are presented below in Figure 19. Figure 19 indicates that EF-Narrow T1 (β = 0.48, *p* = .000) and average grades T1 (β = 0.11, *p* = .000) were significant positive predictors of EF-Narrow T2, with EF-Narrow T1 a stronger predictor than average grades T1. EF-Narrow T1 (β = 0.06, *p* = .001) and average grades T1 (β = 0.56, *p* = .000) were significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Narrow T1. Average grades T1 (β = 0.26, *p* = .000) was significantly positively correlated with EF-Narrow T1, and average grades T2 (β = 0.06, *p* = .015) was significantly positively correlated with EF-Narrow T2, with average grades T1 more strongly correlated with EF-Narrow T1 than average grades T2 of EF-Narrow T2. However, alcohol exposure before knowing of pregnancy was not a significant predictor of EF-Narrow T1/T2 or average grades T1/T2.

Figure 19

Model 11: Simple – Associations Between Alcohol Use, EF-Narrow T1/T2, and Average Grades T1/T2



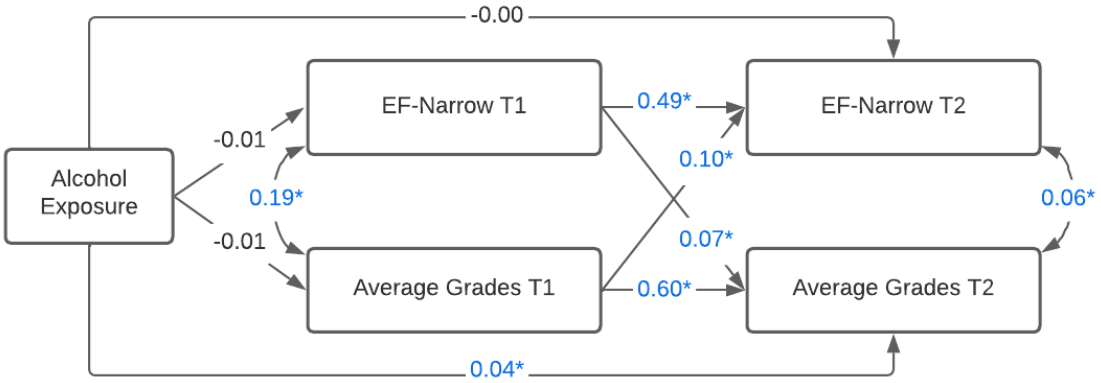
Note. *n* = 2,079. Results of the path analysis for associations between maternal alcohol use before knowing of pregnancy, EF-Narrow T1/T2, and average grades T1/T2. Standardized coefficients are presented.
*$p < .05$

Model 12. Simple + Demographics: Alcohol Use, EF-Narrow, and Average Grades. The results of the simple + demographics path analysis with standardized regression coefficients for alcohol use, EF-Narrow, and average grades, controlling for parental income, education, and marital status, are presented below in Figure 20. Figure 20 indicates that when controlling for demographic variables, EF-Narrow T1 (β = 0.49, *p* = .000) and average grades T1 (β = 0.10, *p* = .000) were significant positive predictors of EF-Narrow T2, with EF-Narrow T1 a stronger predictor than average grades T1. EF-Narrow T1 (β = 0.07, *p* = .001), average grades T1 (β = 0.60, *p* = .000), and alcohol use before knowing of pregnancy (β = 0.04, *p* = .036) were significant *positive* predictors of average grades T2; like the analysis in Model 10 above, average grades T1 was a stronger predictor of average grades T2 than either EF-Narrow T1 or prenatal alcohol use. Average grades T1 (β = 0.19, *p* = .000) was significantly positively correlated with EF-Narrow T1, and average grades T2 (β = 0.06, *p* = .023) was significantly positively correlated with EF-Narrow T2, with average grades T1 more strongly correlated with EF-Narrow T1 than average grades T2 of EF-Narrow T2. However, although alcohol exposure before knowing of pregnancy was a significant *positive* predictor of average grades T2; it was not a significant predictor of EF-Narrow

T1/T2 or average grades T1. Table 31 below presents a summary of the simple and simple + demographics regression results, and Figure 31 in the Appendix presents Models 9 through 12 side-by-side.

Figure 20

Model 12: Simple + Demographics – Associations Between Alcohol Use, EF-Narrow T1/T2, and Average Grades T1/T2



Note. *n* = 2,079. Results of the path analysis for associations between maternal alcohol use before knowing of pregnancy, EF-Narrow T1/T2, and average grades T1/T2, controlling for parental income, education, and marital status. Standardized coefficients are presented.
*$p < .05$

Table 31

Models 11 and 12 Standardized Coefficients and Associated Data

	Simple			Simple + Demographics*		
Variable	Standardized estimate	*SE*	*p*-value	Standardized estimate	*SE*	*p*-value
EF-Narrow T2 ~						
EF-Narrow T1	0.480	0.023	.000	0.485	0.024	.000
Avg grades T1	0.107	0.022	.000	0.104	0.021	.000
Alcohol use	0.002	0.004	.906	-0.001	0.004	.968
Avg grades T2 ~						
EF-Narrow T1	0.064	0.021	.001	0.065	0.021	.001
Avg grades T1	0.556	0.020	.000	0.596	0.019	.000
Alcohol use	0.035	0.004	.063	0.040	0.004	.036

EF-Narrow T1 ~						
Alcohol use	0.025	0.004	.289	-0.012	0.004	.597
Married				0.031	0.039	.170
HS diploma/GED				0.019	0.069	.403
Some college				0.094	0.038	.000
Bachelor				0.189	0.038	.000
Post-graduate				0.166	0.039	.000
≧50K & < 100K				0.073	0.038	.001
≧100K				0.138	0.035	.000
Avg grades T1 ~						
Alcohol use	0.023	0.004	.329	-0.007	0.004	.741
Married				0.054	0.039	.007
HS diploma/GED				0.084	0.069	.000
Some college				0.229	0.038	.000
Bachelor				0.285	0.038	.000
Post-graduate				0.362	0.038	.000
≧50K & < 100K				0.070	0.038	.001
≧100K				0.142	0.035	.000
EF-Narrow T1 ~						
Avg grades T1	0.255	0.014	.000	0.192	0.013	.000
EF-Narrow T2 ~						
Avg grades T2	0.057	0.011	.015	0.055	0.011	.023

Note. *n* = 2,079. Standardized coefficients are presented.
*Reference groups for dummy coded variables: Parental marital status = Not married; Highest parental education = < HS diploma; Household income = < 50K.

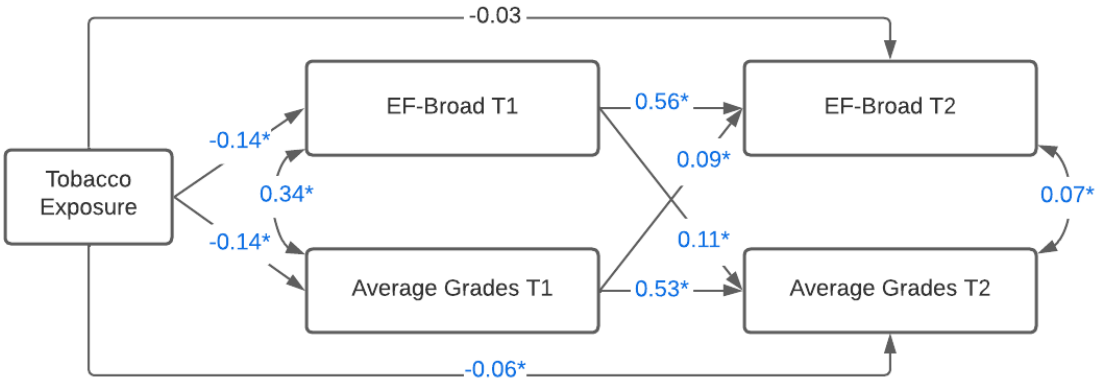
Study 2: Relationship Between Prenatal Tobacco Use, EF-Broad/EF-Narrow, and Average Grades

Model 13. Simple: Tobacco Use, EF-Broad, and Average Grades. The results of the simple path analysis with standardized regression coefficients for tobacco use, EF-Broad, and average grades are presented below in Figure 21. Figure 21 indicates that EF-Broad T1 (β = 0.56, *p* = .000) and average grades T1 (β = 0.09, *p* = .000) were significant positive predictors of EF-Broad T2, with EF-Broad T1 a stronger predictor than average grades T1. Although tobacco use before knowing of pregnancy (β = -0.06, *p* = .002) was a significant *negative* predictor of average grades T2, EF-Broad T1 (β = 0.11, *p* = .000) and average grades T1 (β = 0.53, *p* = .000) were significant *positive* predictors of average grades T2, with average grades T1 a stronger predictor than either EF-Broad T1 or prenatal tobacco use. Tobacco use

before knowing of pregnancy was a significant *negative* predictor of EF-Broad T1 (β = -0.14, *p* = .000) and average grades T1 (β = -0.14, *p* = .000). Average grades T1 (β = 0.34, *p* = .000) was significantly positively correlated with EF-Broad T1, and average grades T2 (β = 0.07, *p* = .004) was significantly positively correlated with EF-Broad T2, with average grades T1 more strongly correlated with EF-Broad T1 than average grades T2 of EF-Broad T2. However, tobacco exposure before knowing of pregnancy was not a significant predictor of EF-Broad T2.

Figure 21

Model 13: Simple – Associations Between Tobacco Use, EF-Broad T1/T2, and Average Grades T1/T2



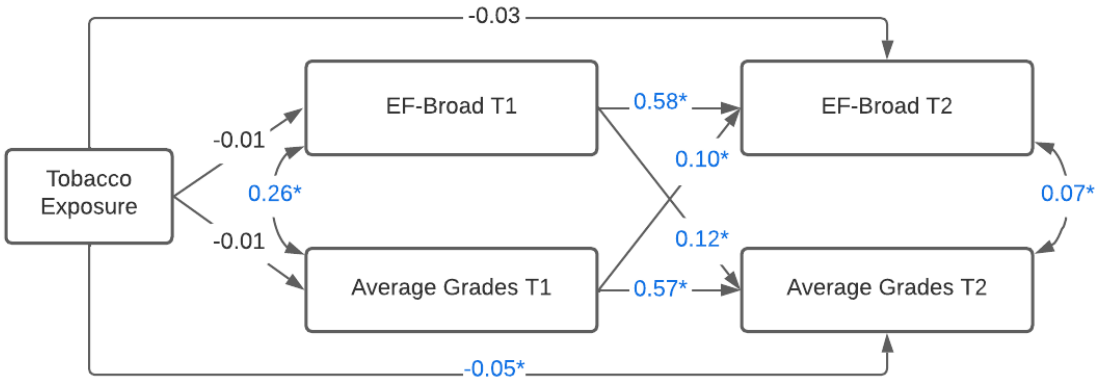
Note. *n* = 2,079. Results of the path analysis for associations between maternal tobacco use before knowing of pregnancy, EF-Broad T1/T2, and average grades T1/T2. Standardized coefficients are presented.
*$p < .05$

Model 14. Simple + Demographics: Tobacco Use, EF-Broad, and Average Grades. The results of the simple + demographics path analysis with standardized regression coefficients for tobacco use, EF-Broad, and average grades, controlling for parental income, education, and marital status, are presented below in Figure 22. Figure 22 indicates that EF-Broad T1 (β = 0.58, *p* = .000) and average grades T1 (β = 0.10, *p* = .000) were significant positive predictors of EF-Broad T2, with EF-Broad T1 a stronger predictor than average grades T1. Although tobacco use before knowing of pregnancy (β = -0.05, *p* = .005) was a significant *negative* predictor of average grades T2, EF-Broad T1 (β = 0.12, *p* = .000) and average grades

T1 (β = 0.57, *p* = .000) were significant *positive* predictors of average grades T2, with average grades T1 a stronger predictor than either EF-Broad T1 or prenatal tobacco use. Average grades T1 (β = 0.26, *p* = .000) was significantly positively correlated with EF-Broad T1, and average grades T2 (β = 0.07, *p* = .003) was significantly positively correlated with EF-Broad T2; like the simple analysis in Model 13 above, average grades T1 was more strongly correlated with EF-Broad T1 than average grades T2 of EF-Broad T2. However, although tobacco exposure before knowing of pregnancy was a significant *negative* predictor of average grades T2; it was not a significant predictor of EF-Broad T1/T2 or average grades T1. Table 32 below presents a summary of the simple and simple + demographics regression results.

Figure 22

Model 14: Simple + Demographics – Associations Between Tobacco Use, EF-Broad T1/T2, and Average Grades T1/T2



Note. *n* = 2,079. Results of the path analysis for associations between maternal tobacco use before knowing of pregnancy, EF-Broad T1/T2, and average grades T1/T2, controlling for parental income, education, and marital status. Standardized coefficients are presented.
*$p < .05$

Table 32

Models 13 and 14 Standardized Coefficients and Associated Data

	Simple			Simple + Demographics*		
Variable	Standardized estimate	*SE*	*p*-value	Standardized estimate	*SE*	*p*-value

EF-Broad T2 ~						
EF-Broad T1	0.557	0.022	.000	0.576	0.022	.000
Avg grades T1	0.093	0.018	.000	0.095	0.018	.000
Tobacco use	-0.034	0.002	.071	-0.034	0.002	.068
Avg grades T2 ~						
EF-Broad T1	0.108	0.025	.000	0.115	0.025	.000
Avg grades T1	0.533	0.020	.000	0.574	0.019	.000
Tobacco use	-0.059	0.003	.002	-0.052	0.003	.005
EF-Broad T1 ~						
Tobacco use	-0.144	0.003	.000	-0.009	0.002	.667
Married				0.043	0.031	.034
HS diploma/GED				0.081	0.056	.000
Some college				0.186	0.031	.000
Bachelor				0.296	0.031	.000
Post-graduate				0.305	0.031	.000
≧50K & < 100K				0.085	0.031	.000
≧100K				0.150	0.028	.000
Avg grades T1 ~						
Tobacco use	-0.137	0.003	.000	-0.006	0.003	.761
Married				0.054	0.038	.006
HS diploma/GED				0.095	0.068	.000
Some college				0.247	0.037	.000
Bachelor				0.296	0.038	.000
Post-graduate				0.368	0.038	.000
≧50K & < 100K				0.062	0.037	.002
≧100K				0.133	0.034	.000
EF-Broad T1 ~						
Avg grades T1	0.337	0.012	.000	0.263	0.011	.000
EF-Broad T2 ~						
Avg grades T2	0.067	0.009	.004	0.071	0.026	.003

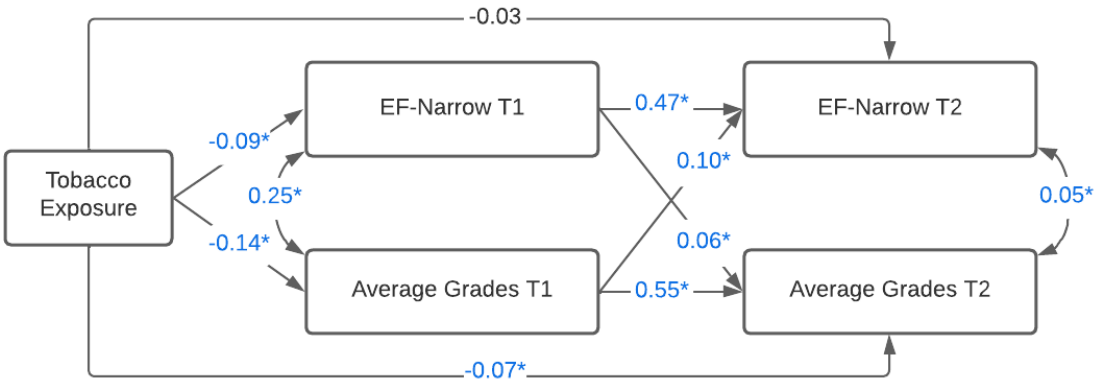
Note. *n* = 2,079. Standardized coefficients are presented.
*Reference groups for dummy coded variables: Parental marital status = Not married; Highest parental education = < HS diploma; Household income = < 50K.

Model 15. Simple: Tobacco Use, EF-Narrow, and Average Grades. The results of the simple path analysis with standardized regression coefficients for tobacco use, EF-Narrow, and average grades are presented below in Figure 23. Figure 23 indicates that EF-Narrow T1 (β = 0.47, *p* = .000) and average grades T1 (β = 0.10, *p* = .000) were significant positive predictors of EF-Narrow T2, with EF-Narrow T1 a

stronger predictor than average grades T1. Although tobacco use before knowing of pregnancy (β = -0.07, *p* = .000) was a significant *negative* predictor of average grades T2, EF-Narrow T1 (β = 0.06, *p* = .001) and average grades T1 (β = 0.55, *p* = .000) were significant *positive* predictors of average grades T2, with average grades T1 a stronger predictor than either EF-Narrow T1 or prenatal tobacco use. Tobacco use before knowing of pregnancy was a significant *negative* predictor of EF-Narrow T1 (β = -0.09, *p* = .000) and average grades T1 (β = -0.14, *p* = .000), with prenatal tobacco use a stronger predictor of average grades T1 than of EF-Narrow T1. Average grades T1 (β = 0.25, *p* = .000) was significantly positively correlated with EF-Narrow T1, and average grades T2 (β = 0.03, *p* = .019) was significantly positively correlated with EF-Narrow T2, with average grades T1 more strongly correlated with EF-Narrow T1 than average grades T2 of EF-Narrow T2. However, tobacco exposure before knowing of pregnancy was not a significant predictor of EF-Narrow T2.

Figure 23

Model 15: Simple – Associations Between Tobacco Use, EF-Narrow T1/T2, and Average Grades T1/T2

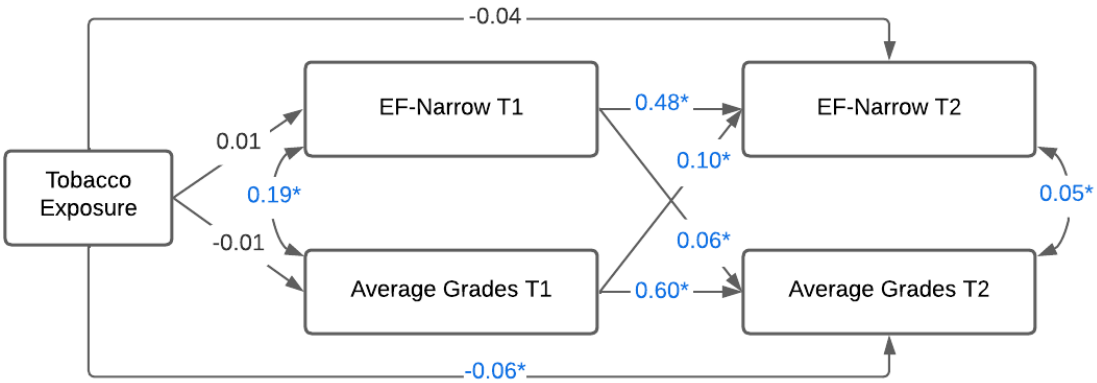


Note. *n* = 2,079. Results of the path analysis for associations between maternal tobacco use before knowing of pregnancy, EF-Narrow T1/T2, and average grades T1/T2. Standardized coefficients are presented.
*$p < .05$

Model 16. Simple + Demographics: Tobacco Use, EF-Narrow, and Average Grades. The results of the simple + demographics path analysis with standardized regression coefficients for tobacco use, EF-Narrow, and average grades, controlling for parental income, education, and marital status, are presented below in Figure 24. Figure 24 indicates that EF-Narrow T1 (β = 0.48, *p* = .000) and average grades T1 (β = 0.10, *p* = .000) were significant positive predictors of EF-Narrow T2, with EF-Narrow T1 a stronger predictor than average grades T1. Though not significant to *p* < .05, tobacco use before knowing pregnancy (β = -0.04, *p* = .058) was a marginal *negative* predictor of EF-Narrow T2. Although tobacco use before knowing of pregnancy (β = -0.06, *p* = .001) was a significant *negative* predictor of average grades T2, EF-Narrow T1 (β = 0.06, *p* = .002) and average grades T1 (β = 0.60, *p* = .000) were significant *positive* predictors of average grades T2, with average grades T1 a stronger predictor than either EF-Narrow T1 or prenatal tobacco use. Average grades T1 (β = 0.19, *p* = .000) was significantly positively correlated with EF-Narrow T1, and average grades T2 (β = 0.05, *p* = .028) was significantly positively correlated with EF-Narrow T2; like the simple analysis in Model 15 above, average grades T1 was more strongly correlated with EF-Narrow T1 than average grades T2 of EF-Narrow T2. However, although tobacco exposure before knowing of pregnancy was a significant *negative* predictor of average grades T2; it was not a significant predictor of EF-Narrow T1/T2 or average grades T1. Table 33 below presents a summary of the simple and simple + demographics regression results, and Figure 32 in the Appendix presents Models 13 through 16 side-by-side.

Figure 24

Model 16: Simple + Demographics – Associations Between Tobacco Use, EF-Narrow T1/T2, and Average Grades T1/T2



Note. *n* = 2,079. Results of the path analysis for associations between maternal tobacco use before knowing of pregnancy, EF-Narrow T1/T2, and average grades T1/T2, controlling for parental income, education, and marital status. Standardized coefficients are presented.
*$p < .05$

Table 33

Models 15 and 16 Standardized Coefficients and Associated Data

	Simple			Simple + Demographics*		
Variable	Standardized estimate	*SE*	*p*-value	Standardized estimate	*SE*	*p*-value
EF-Narrow T2 ~						
EF-Narrow T1	0.474	0.022	.000	0.480	0.023	.000
Avg grades T1	0.104	0.022	.000	0.100	0.020	.000
Tobacco use	-0.033	0.003	.101	-0.038	0.003	.058
Avg grades T2 ~						
EF-Narrow T1	0.062	0.020	.001	0.062	0.021	.002
Avg grades T1	0.554	0.020	.000	0.602	0.018	.000
Tobacco use	-0.066	0.003	.000	-0.059	0.003	.001
EF-Narrow T1 ~						
Tobacco use	-0.089	0.003	.000	0.014	0.003	.535
Married				0.031	0.038	.164
HS diploma/GED				0.029	0.069	.195
Some college				0.089	0.038	.000
Bachelor				0.185	0.038	.000
Post-graduate				0.163	0.038	.000
≧50K & < 100K				0.079	0.038	.000
≧100K				0.149	0.035	.000
Avg grades T1 ~						

Tobacco use	-0.137	0.003	.000	-0.006	0.003	.761
Married				0.054	0.038	.006
HS diploma/GED				0.095	0.068	.000
Some college				0.247	0.037	.000
Bachelor				0.296	0.038	.000
Post-graduate				0.368	0.038	.000
≧50K & < 100K				0.062	0.037	.002
≧100K				0.133	0.034	.000
EF-Narrow T1 ~						
Avg grades T1	0.245	0.014	.000	0.189	0.013	.000
EF-Narrow T2 ~						
Avg grades T2	0.054	0.011	.019	0.052	0.011	.028

Note. *n* = 2,079. Standardized coefficients are presented.
*Reference groups for dummy coded variables: Parental marital status = Not married; Highest parental education = < HS diploma; Household income = < 50K.

Study 3: Relationship Between Combined Use (Alcohol AND Tobacco), EF-Broad/EF-Narrow, and Average Grades

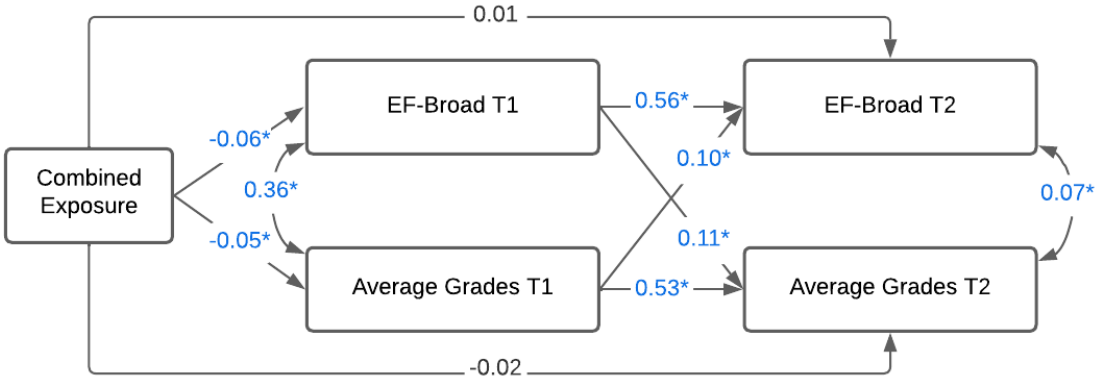
As previously discussed, in contrast to the alcohol use only and tobacco use only models presented above, the combined use analyses used a dummy coded variable [1 = combined use (use of both alcohol AND tobacco during pregnancy); 0 = no combined use], whereby only parents who reported maternal use of both substances during pregnancy were coded as 1 (i.e., combined use), and included in these analyses.

Model 17. Simple: Combined Use, EF-Broad, and Average Grades. The results of the simple path analysis with standardized regression coefficients for combined use, EF-Broad, and average grades are presented below in Figure 25. Figure 25 indicates that EF-Broad T1 (β = 0.56, *p* = .000) and average grades T1 (β = 0.10, *p* = .000) were significant positive predictors of EF-Broad T2, with EF-Broad T1 a stronger predictor than average grades T1. EF-Broad T1 (β = 0.11, *p* = .000) and average grades T1 (β = 0.53, *p* = .000) were significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Broad T1. Combined use before knowing of pregnancy was a significant *negative* predictor of EF-Broad T1 (β = -0.06, *p* = .016) and average grades T1 (β = -0.05, *p* = .047).

Average grades T1 (β = 0.36, *p* = .000) was significantly positively correlated with EF-Broad T1, and average grades T2 (β = 0.07, *p* = .004) was significantly positively correlated with EF-Broad T2, with average grades T1 more strongly correlated with EF-Broad T1 than average grades T2 of EF-Broad T2. However, combined exposure before knowing of pregnancy was not a significant predictor of EF-Broad T2 or average grades T2.

Figure 25

Model 17: Simple – Associations Between Combined Use, EF-Broad T1/T2, and Average Grades T1/T2



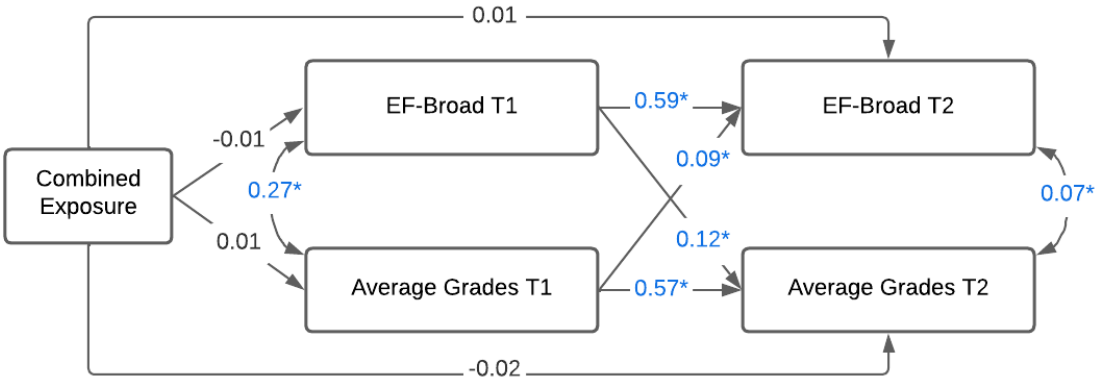
Note. *n* = 2,079. Results of the path analysis for associations between maternal combined use before knowing of pregnancy, EF-Broad T1/T2, and average grades T1/T2. Standardized coefficients are presented.
*$p < .05$

Model 18. Simple + Demographics: Combined Use, EF-Broad, and Average Grades. The results of the simple + demographics path analysis with standardized regression coefficients for combined use, EF-Broad, and average grades, controlling for parental income, education, and marital status, are presented below in Figure 26. Figure 26 indicates that EF-Broad T1 (β = 0.59, *p* = .000) and average grades T1 (β = 0.09, *p* = .000) were significant positive predictors of EF-Broad T2, with EF-Broad T1 a stronger predictor than average grades T1. EF-Broad T1 (β = 0.12, *p* = .000) and average grades T1 (β = 0.57, *p* = .000) were significant positive predictors of average grades T2, with average grades T1 a

stronger predictor than EF-Broad T1. Average grades T1 (β = 0.27, *p* = .000) was significantly positively correlated with EF-Broad T1, and average grades T2 (β = 0.07, *p* = .003) was significantly positively correlated with EF-Broad T2; like the simple analysis in Model 17 above, average grades T1 was more strongly correlated with EF-Broad T1 than average grades T2 of EF-Broad T2. However, combined exposure before knowing of pregnancy was not a significant predictor of EF-Broad T1/T2 or average grades T1/T2. Table 34 below presents a summary of the simple and simple + demographics regression results.

Figure 26

Model 18: Simple + Demographics – Associations Between Combined Use, EF-Broad T1/T2, and Average Grades T1/T2



Note. *n* = 2,079. Results of the path analysis for associations between maternal combined use before knowing of pregnancy, EF-Broad T1/T2, and average grades T1/T2, controlling for parental income, education, and marital status. Standardized coefficients are presented.
*$p < .05$

Table 34

Models 17 and 18 Standardized Coefficients and Associated Data

	Simple			Simple + Demographics*		
Variable	Standardized estimate	*SE*	*p*-value	Standardized estimate	*SE*	*p*-value
EF-Broad T2 ~						

EF-Broad T1	0.564	0.023	.000	0.586	0.023	.000
Avg grades T1	0.095	0.019	.000	0.094	0.018	.000
Combined use	0.014	0.035	.453	0.012	0.036	.512
Avg grades T2 ~						
EF-Broad T1	0.113	0.026	.000	0.121	0.025	.000
Avg grades T1	0.534	0.021	.000	0.567	0.020	.000
Combined use	-0.022	0.039	.259	-0.018	0.040	.333
EF-Broad T1 ~						
Combined use	-0.056	0.039	.016	-0.019	0.037	.366
Married				0.034	0.032	.101
HS diploma/GED				0.077	0.058	.000
Some college				0.197	0.031	.000
Bachelor				0.305	0.031	.000
Post-graduate				0.316	0.031	.000
≧50K & < 100K				0.081	0.031	.000
≧100K				0.150	0.029	.000
Avg grades T1 ~						
Combined use	-0.047	0.047	.047	0.012	0.045	.565
Married				0.053	0.039	.009
HS diploma/GED				0.081	0.071	.000
Some college				0.226	0.038	.000
Bachelor				0.287	0.038	.000
Post-graduate				0.361	0.038	.000
≧50K & < 100K				0.068	0.038	.001
≧100K				0.145	0.035	.000
EF-Broad T1 ~						
Avg grades T1	0.355	0.012	.000	0.272	0.011	.000
EF-Broad T2 ~						
Avg grades T2	0.068	0.009	.004	0.072	0.009	.003

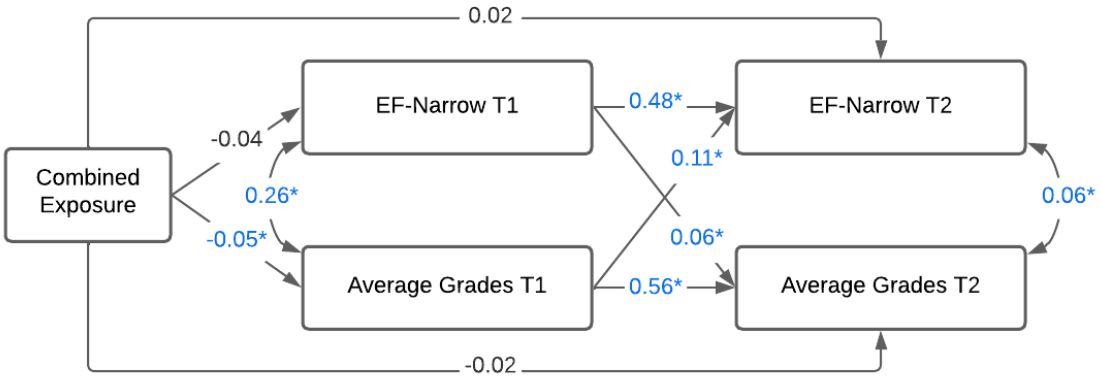
Note. *n* = 2,079. Standardized coefficients are presented.
*Reference groups for dummy coded variables: Parental marital status = Not married; Highest parental education = < HS diploma; Household income = < 50K.

Model 19. Simple: Combined Use, EF-Narrow, and Average Grades. The results of the simple path analysis with standardized regression coefficients for combined use, EF-Narrow, and average grades are presented below in Figure 27. Figure 27 indicates that EF-Narrow T1 (β = 0.48, *p* = .000) and average grades T1 (β = 0.11, *p* = .000) were significant positive predictors of EF-Narrow T2, with EF-Narrow T1 a stronger predictor than average grades T1. EF-Narrow T1 (β = 0.06, *p* = .001) and average

grades T1 (β = 0.56, *p* = .000) were significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Narrow T1. Combined use before knowing of pregnancy was a significant *negative* predictor of average grades T1 (β = -0.05, *p* = .047). Average grades T1 (β = 0.26, *p* = .000) was significantly positively correlated with EF-Narrow T1, and average grades T2 (β = 0.06, *p* = .015) was significantly positively correlated with EF-Narrow T2, with average grades T1 more strongly correlated with EF-Narrow T1 than average grades T2 of EF-Narrow T2. However, combined exposure before knowing of pregnancy was not a significant predictor of EF-Narrow T1/T2 or average grades T2.

Figure 27

Model 19: Simple – Associations Between Combined Use, EF-Narrow T1/T2, and Average Grades T1/T2



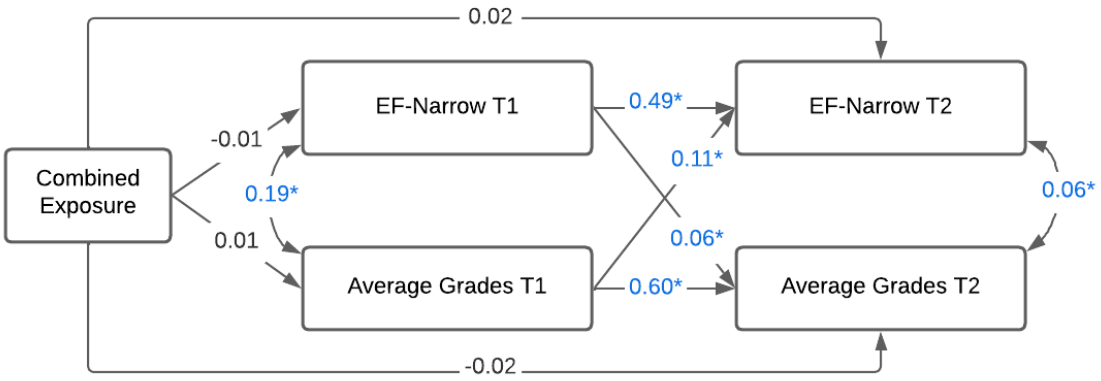
Note. *n* = 2,079. Results of the path analysis for associations between maternal combined use before knowing of pregnancy, EF-Narrow T1/T2, and average grades T1/T2. Standardized coefficients are presented.
*$p < .05$

Model 20. Simple + Demographics: Combined Use, EF-Narrow, and Average Grades. The results of the simple + demographics path analysis with standardized regression coefficients for combined use, EF-Narrow, and average grades, controlling for parental income, education, and marital status, are presented below in Figure 28. Figure 28 indicates that EF-Narrow T1 (β = 0.49, *p* = .000) and average grades T1 (β = 0.11, *p* = .000) were significant positive predictors of EF-Narrow T2, with EF-

Narrow T1 a stronger predictor than average grades T1. EF-Narrow T1 (β = 0.06, *p* = .002) and average grades T1 (β = 0.60, *p* = .000) were significant positive predictors of average grades T2, with average grades T1 a stronger predictor than EF-Narrow T1. Average grades T1 (β = 0.19, *p* = .000) was significantly positively correlated with EF-Narrow T1, and average grades T2 (β = 0.06, *p* = .023) was significantly positively correlated with EF-Narrow T2; like the simple analysis in Model 19 above, average grades T1 was more strongly correlated with EF-Narrow T1 than average grades T2 of EF-Narrow T2. However, combined exposure before knowing of pregnancy was not a significant predictor of EF-Narrow T1/T2 or average grades T1/T2. Table 35 below presents a summary of the simple and simple + demographics regression results, and Figure 33 in the Appendix presents Models 17 through 20 side-by-side.

Figure 28

Model 20: Simple + Demographics – Associations Between Combined Use, EF-Narrow T1/T2, and Average Grades T1/T2



Note. *n* = 2,079. Results of the path analysis for associations between maternal combined use before knowing of pregnancy, EF-Narrow T1/T2, and average grades T1/T2, controlling for parental income, education, and marital status. Standardized coefficients are presented.
*$p < .05$

Table 35

Models 19 and 20 Standardized Coefficients and Associated Data

	Simple			Simple + Demographics*		
Variable	Standardized estimate	*SE*	*p*-value	Standardized estimate	*SE*	*p*-value
EF-Narrow T2 ~						
EF-Narrow T1	0.481	0.023	.000	0.485	0.024	.000
Avg grades T1	0.110	0.022	.000	0.105	0.021	.000
Combined use	0.026	0.043	.197	0.021	0.044	.310
Avg grades T2 ~						
EF-Narrow T1	0.063	0.021	.001	0.063	0.021	.002
Avg grades T1	0.558	0.020	.000	0.598	0.019	.000
Combined use	-0.024	0.039	.204	-0.022	0.040	.239
EF-Narrow T1 ~						
Combined use	-0.038	0.046	.101	-0.011	0.045	.628
Married				0.027	0.039	.248
HS diploma/GED				0.022	0.071	.345
Some college				0.089	0.038	.000
Bachelor				0.185	0.038	.000
Post-graduate				0.161	0.039	.000
≧50K & < 100K				0.074	0.038	.001
≧100K				0.140	0.035	.000
Avg grades T1 ~						
Combined use	-0.047	0.047	.047	0.012	0.045	.565
Married				0.053	0.039	.009
HS diploma/GED				0.081	0.071	.000
Some college				0.226	0.038	.000
Bachelor				0.287	0.038	.000
Post-graduate				0.361	0.038	.000
≧50K & < 100K				0.068	0.038	.001
≧100K				0.145	0.035	.000
EF-Narrow T1 ~						
Avg grades T1	0.255	0.014	.000	0.193	0.013	.000
EF-Narrow T2 ~						
Avg grades T2	0.057	0.011	.015	0.055	0.011	.023

Note. *n* = 2,079. Standardized coefficients are presented.

*Reference groups for dummy coded variables: Parental marital status = Not married; Highest parental education = < HS diploma; Household income = < 50K.

4. Discussion

The primary goal of the current study was to explore the association between low-to-moderate prenatal alcohol and/or tobacco exposure and adolescents' subsequent EF and academic performance at two separate time points in their development. Using longitudinal data from the ABCD Study (i.e., data from the baseline and 2-year follow-up collection periods), the present study examined whether prenatal alcohol and/or tobacco exposure was associated with negative effects on adolescents' performances on various EF tasks (using the NIHTB-CB) and/or their average grades in school. Additionally, given that EF has not been consistently defined within the psychological literature, with the field of developmental psychology defining EF more broadly (i.e., cognitive flexibility, working memory, and inhibitory control) and cognitive psychology researchers defining EF more narrowly (i.e., viewing WM as a higher-level, superordinate construct that is separate from EF), this study explored these competing perspectives by examining EF from both perspectives (EF-Broad and EF-Narrow).

The overarching prediction was that when EF was broadly defined, adolescents who were prenatally exposed to alcohol and/or tobacco would exhibit stronger effects (i.e., a greater reduction in performance on EF tasks and average grades) than when EF was narrowly defined. If this prediction held true, then any reduced performance when EF was broadly defined would mean that differences between the analyses were due to the relationship between WM and teratogen exposure. Three separate studies, distinguished by types of exposure (i.e., alcohol, tobacco, combined), explored this overarching prediction.

4.1. Study 1: Relationship Between Prenatal Alcohol Use, EF-Broad/EF-Narrow, and Average Grades

For Study 1, PAE was hypothesized to be associated with reduced EF task performance (EF-Broad and EF-Narrow) and reduced average grades at both time 1 and time 2, with a greater reduction in EF task performance in the EF-Broad models. Two sets of path analyses were conducted looking at PAE; one set explored low-to-moderate alcohol exposure using constrained models with a dataset

exclusively focused on parent-reported prenatal alcohol use before knowing of pregnancy (*n* = 1,508), and the other set examined the full sample dataset (*n* = 2,079), which included parent-reported prenatal alcohol use above the specified low-to-moderate range (i.e., alcohol use of >0 to 8 drinks on average per week).

4.1.1. Low-to-Moderate Alcohol Exposure

Results of the low-to-moderate analyses did not support the prediction. More specifically, low-to-moderate PAE was not a significant predictor of EF-Broad T1/T2 or EF-Narrow T1/T2, nor was it a significant predictor of average grades T1/T2. These null findings are consistent with other research and meta-analyses reporting no associations between low-to-moderate PAE and EF or other areas of cognition (Römer et al., 2020; Skogerbø et al., 2012); though some studies have reported findings demonstrating reduced academic performance and attention-related difficulties (Alati et al., 2013; Lees et al., 2020), and others have reported better inhibitory and attention capabilities and improved academic performance (Lees et al., 2020; Olson et al., 1997; Todorow et al., 2010; Zuccolo et al., 2013). Nonetheless, other interesting findings did emerge in these analyses. For example, in both the simple model and the simple + demographics model, EF-Broad T1 AND average grades T1 were *both* positive predictors of EF-Broad T2 AND average grades T2. These findings were also found in the EF-Narrow analyses; however, when compared with the EF-Narrow analyses, the EF-Broad T1 analyses resulted in stronger associations between EF-Broad AND average grades T2 than those found in the EF-Narrow T1 results, suggesting stronger relationships between the EF composites containing the WM tasks (EF-Broad) than the EF composites without the WM tasks (EF-Narrow). Prior to conducting the path analyses, the correlations between EF-Broad T1/T2, EF-Narrow T1/T2, and average grades T1/T2 (see Table 24) revealed similar findings; average grades T1/T2 were more strongly correlated with EF-Broad T1/T2 than with EF-Narrow T1/T2. These findings are consistent with other research that has indicated that EFs contribute to and are considered to be good predictors of academic performance in normally

developed primary and middle school-aged children, with WM exhibiting more predictive weight than other aspects of EF when looking at academic achievement (Cortés Pascual et al., 2019; Samuels et al., 2016).

Furthermore, average grades T1 was positively correlated with EF-Broad T1 AND EF-Narrow T1. Similar correlations were also found between average grades T2 and EF-Broad T2 AND EF-Narrow T2. These additional findings suggest a bidirectional relationship between average grades and EF, whereby executive functioning is positively correlated with academic performance, and vice versa.

4.1.2. Full Sample Dataset Alcohol Exposure

For comparative purposes, an additional set of path analyses was conducted using the full sample dataset (*n* = 2,079). The results of these analyses were similar to the low-to-moderate results presented above with one notable exception. Interestingly, in both the EF-Broad and EF-Narrow models controlling for demographics (i.e., parental income, education, and marital status) but not the simple models, PAE was *positively* associated with average grades T2, implying that substance exposure in utero had a small, but significant relationship with *improved* academic performance during the 2-year follow-up collection period, but not during the baseline collection period. This relationship emerged only after controlling for demographic variables. The longitudinal aspects of this finding are consistent with a longitudinal study reported by Olson et al. (1997), who found that children at 8 months or at 7 years of age did not exhibit alcohol-related deficiencies, but by age 14 years, alcohol-related cognitive and behavioral dysfunctions were observable. Of course, a crucial difference between Olson et al.'s findings and the results presented here is the direction of the relationship between alcohol exposure and long-term outcomes. Olson et al. reported *deficits* due to PAE, whereas the current results suggest significant *positive* academic outcomes for adolescents prenatally exposed to alcohol. These contradictory findings are consistent with the literature examining low-to-moderate PAE, where some studies have reported reduced academic outcomes, lower scores on cognitive tasks, and lower IQ scores related to low-to-

moderate PAE (Alati et al., 2013; Jensen et al., 2015; Lees et al., 2020; Mamluk et al., 2017; Olson et al., 1997; Polańska et al., 2015), and other studies have reported higher IQ scores, improved academic performance, and better inhibitory and attention capabilities (Lees et al., 2020; Olson et al., 1997; Todorow et al., 2010; Zuccolo et al., 2013). Taken together, these results suggest that more research is needed in this area.

4.2. Study 2: Relationship Between Prenatal Tobacco Use, EF-Broad/EF-Narrow, and Average Grades

For Study 2, PTE was hypothesized to be associated with reduced EF task performance (EF-Broad and EF-Narrow) and reduced average grades at both time 1 and time 2, with a greater reduction in EF task performance in the EF-Broad models. Similar to Study 1 which looked at PAE, two sets of path analyses were conducted looking at PTE; one set explored low-to-moderate tobacco exposure using constrained models with a dataset exclusively focused on parent-reported prenatal tobacco use before knowing of pregnancy (*n* = 688), and the other set examined the full sample dataset (*n* = 2,079), which included parent-reported prenatal tobacco use above the specified low-to-moderate range (i.e., tobacco use of >0 to 10 cigarettes per day).

4.2.1. Low-to-Moderate Tobacco Exposure

Like the low-to-moderate results presented above related to PAE, results of the analyses associated with low-to-moderate PTE did not support the prediction. More specifically, low-to-moderate PTE was not a significant predictor of EF-Broad T1/T2 or EF-Narrow T1/T2, nor was it a significant predictor of average grades T1/T2. These null findings are *inconsistent* with studies that have generally reported *negative* effects of low-to-moderate amounts of PTE (Julvez et al., 2007; Römer et al., 2020). However, given the small number of studies focused on low-to-moderate prenatal tobacco use (most research to date has focused on high-level tobacco use), further research is needed to understand these conflicting findings. In contrast to these null results, significant findings similar to those found with low-to-moderate PAE did emerge.

First, in both the simple and simple + demographics models, EF-Broad T1 AND average grades T1 were *both* positive predictors of EF-Broad T2 AND average grades T2. Like the EF-Broad models, in the EF-Narrow analyses (both the simple model and the simple + demographics model), average grades T1 was a positive predictor of EF-Narrow T2 AND average grades T2. However, unlike the EF-Broad models, EF-Narrow T1 was not a significant predictor of average grades T2, though EF-Narrow T1 was a positive predictor of EF-Narrow T2. Given that the primary difference between the EF-Broad composites and the EF-Narrow composites was the absence of the WM tasks in the latter, this finding is consistent with the finding noted above in Study 1 suggesting that WM may hold more predictive weight in the relationship between EF and academic achievement (Cortés Pascual et al., 2019). More specifically, in the absence of the WM tasks, the EF-Narrow T1 measure did not appear to serve as a reliable predictor of average grades T2 in children prenatally exposed to low-to-moderate tobacco.

Second, average grades T1 was positively correlated with EF-Broad T1 (simple: $\beta = 0.37$; simple + demographics: $\beta = 0.30$) and EF-Narrow T1 (simple: $\beta = 0.26$; simple + demographics: $\beta = 0.21$). However, these findings were not found between average grades T2 and EF-Broad T2 OR average grades T2 and EF-Narrow T2. These additional findings suggest that the bidirectional relationship that exists between average grades T1 and EF T1 (both Broad and Narrow) did not characterize the relationship between average grades and EF by the time the 2-year follow-up collection period occurred. Given the moderately high correlations between average grades T1 and EF-Broad T1, it is unclear why these relationships do not exist in the 2-year follow-up data.

4.2.2. Full Sample Dataset Tobacco Exposure

For comparative purposes, an additional set of path analyses was conducted using the full sample dataset (*n* = 2,079), which, as a reminder, included participants exposed to more than low-to-moderate levels of tobacco. The results of these analyses were similar to the low-to-moderate results presented above, with a few notable exceptions.

First, in the simple analyses (not controlling for demographic variables) of both the EF-Broad AND EF-Narrow data, PTE was *negatively* associated with EF-Broad T1, EF-Narrow T1, and average grades T1, albeit with small effect sizes, suggesting that tobacco exposure in utero had a small, but significant association with adverse EF and academic outcomes for adolescents in the baseline collection period; these findings did not hold in the analyses that controlled for parental income, education, and marital status. However, as was predicted (but not found in the low-to-moderate analyses), PTE did result in a greater reduction in EF task performance in the EF-Broad model when compared with the EF-Narrow model ($\beta = -0.14$ versus $\beta = -0.09$, respectively), suggesting a relationship between WM and PTE. Furthermore, in the simple and simple + demographics analyses, in both the EF-Broad AND EF-Narrow models, PTE was associated with lower average grades in adolescents during the 2-year follow-up collection period, again with small effect sizes.

Overall, these findings suggest that PTE may be associated with detrimental outcomes related to EF (particularly at younger ages) and for longer-term academic performance in adolescents. Moreover, consistent with the literature on PTE, these findings indicate negative relationships between PTE and both cognitive functioning (Bennett et al., 2009; Cornelius et al., 2007; Cornelius et al., 2011; Jacobsen et al., 2006; Kotimaa et al., 2003; Langley et al., 2007; Lindblad & Hjern, 2010) and academic performance (Agrawal et al., 2010; Bennett et al., 2013; Fried et al., 1992; Fried & Watkinson, 1990).

4.3. Study 3: Relationship Between Combined Use (Alcohol AND Tobacco), EF-Broad/EF-Narrow, and Average Grades

For Study 3, combined prenatal alcohol AND tobacco exposure was hypothesized to be associated with reduced EF task performance (EF-Broad and EF-Narrow) and reduced average grades at both time 1 and time 2, with a greater reduction in EF task performance in the EF-Broad models. Unlike Studies 1 and 2 above, combined prenatal alcohol AND tobacco exposure was measured using a dummy coded variable [1 = combined use (use of both alcohol AND tobacco during pregnancy); 0 = no combined

use]. Because quantity of use was not taken into consideration in the combined use analyses (i.e., all parents who reported use of both alcohol AND tobacco during pregnancy were included the analyses), only the full sample dataset was examined (*n* = 2,079); low-to-moderate analyses were not possible given the use of a binary variable.

4.3.1. Full Sample Dataset Combined Exposure

Results of the combined use analyses were mixed in terms of supporting the prediction. First, in the simple analyses (i.e., not controlling for demographic variables) for *both* EF-Broad and EF-Narrow, prenatal combined exposure was negatively associated with average grades T1, though with small effect sizes, suggesting that combined exposure in utero had a small, but significant relationship with reduced academic outcomes for adolescents in the baseline collection period. These findings did not hold when controlling for parental income, education, and marital status, nor did they extend to average grades T2. These results may imply a stronger relationship between prenatal combined exposure and early developmental outcomes versus later outcomes. However, the fact that these findings did not hold when controlling for demographic variables, may mean that these effects are associated with parental demographic characteristics. In this particular instance, significant positive relationships were found in the path analyses between the parent demographics (i.e., income, education, and marital status) and EF (Broad and Narrow) and average grades.

Second, prior to controlling for demographic variables, prenatal combined exposure was also negatively associated with EF-Broad T1 (again with a small effect size), but combined exposure was *not* associated with EF-Narrow T1. This finding is another example demonstrating that the absence of the WM tasks in the EF-Narrow composites may play an important role. In this case, the more broadly defined measure of EF (EF-Broad) yielded a greater negative (and significant) relationship with combined prenatal exposure than did the more narrowly defined measure of EF (EF-Narrow); this suggests that WM may be adversely affected by prenatal exposure to a combination of alcohol and tobacco. Given the

lack of research on the combined use of alcohol and tobacco during pregnancy (Dew et al., 2007; Negrão et al., 2021), more research is needed to understand and interpret these findings.

4.4. Limitations and Future Directions

There are obvious benefits to analyzing data from the ABCD Study. For example, the sample population is very diverse, and the dataset is extremely large, with dozens of measures in a variety of psychological domains. However, there are also some noteworthy limitations that affected the present analyses. First, the analyses were restricted to the tasks contained in the NIHTB-CB, which are limited to individual measures focused on specific areas of cognition (e.g., LSWM measures WM, DCCS measures EF and cognitive flexibility, FICA measures inhibitory control and attention, PCPS measures visual processing speed, and PSMT measures episodic memory). Within the field of psychometrics, it is generally accepted that in order to best measure a construct (e.g., WM), multiple items/tasks are required to establish the validity of that construct, with three or more items/tasks regarded as an appropriate benchmark to provide useful statistical information (El-Den et al., 2020). Given the composition of the NIHTB-CB, multiple measures of each cognitive construct are not available, weakening the construct validity of each measure. Further complicating the present analyses, two NIHTB-CB tasks designed to measure EF and WM were omitted from the 2-year follow-up collection period (i.e., LSWM and DCCS).

Additionally, though the ABCD Study is longitudinal in nature and the present study analyzed data from the baseline and 2-year follow-up collection periods, the time between these two collection points reflects a brief period of development with some overlap in participant ages (baseline ages: 8.9 to 11.0 years; 2-year follow-up ages: 10.6 to 13.8 years), making it difficult to evaluate differences associated with cognitive development between adolescents at baseline versus the 2-year follow-up. Given that the ABCD Study is projected to follow this large group of adolescents for 10 years, future

studies will have the opportunity to examine more distinct stages of development and explore differences between those groups.

As might be expected in a study of this magnitude, some of the data collected in the ABCD Study are based on self-reported or parent-reported (on behalf of the child) questionnaires. For example, in the present study, average grades at baseline and the 2-year follow-up collection periods were provided by parents/guardians, making this information less reliable than if it had been obtained directly from the child's school records. Furthermore, the data associated with prenatal substance use were based on parent/guardian-reported maternal use (meaning either a parent or a guardian may have provided this information). Given the social stigma associated with drinking and/or smoking during pregnancy and the social desirability bias associated with participation in research studies, self-report data of this nature may be inaccurate (specifically, substance use may be under-reported) (England et al., 2020). For example, in a sample of more than 3,000 new mothers considered high risk for drug abuse, 44% tested positive for illicit drug use, yet only 11% acknowledged such use (Anderson & Choonara, 2007).

Though under-reporting of illicit drug use may be understandable given the legal implications of such use, low-to-moderate use has its own complications. For example, studies reporting data on the prevalence of prenatal substance use often fail to include the time period between conception and verification of pregnancy (i.e., before knowing of pregnancy), meaning the prevalence of such use is often underestimated and under-reported, especially as it pertains to low-to-moderate use (Römer et al., 2020).

Further, though defining low-to-moderate substance use in the present study was informed by prior research [i.e., >0 to 8 drinks on average per week (Skogerbø et al., 2012; Underbjerg et al., 2012); >0 to 10 cigarettes per day (Kataoka et al., 2018)], the frequency distributions of prenatal alcohol use and prenatal tobacco use in the sampled populations were quite different. For instance, low-to-moderate alcohol use was skewed more toward the lower end of the range, with more parents

reporting 1 to 2 drinks on average per week (*n* = 639), as opposed to 7 to 8 drinks on average per week at the moderate end of the scale (*n* = 88). In contrast, low-to-moderate tobacco use was skewed more toward the higher end of the range, with more parents reporting 9 to 10 cigarettes per day (*n* = 196) versus 1 to 2 cigarettes per day at the lower end of the scale (*n* = 110). These opposing skewed distributions may account for the positive versus negative relationships found between substance exposure and EF/academic outcomes. For example, although the relationships between PTE and EF/average grades were not significant, most of the paths in the models revealed negative relationships, implying possible impairments in EF/academic outcomes. In contrast, in the alcohol use models, several of the paths showed positive (non-significant) relationships between PAE and EF/average grades, implying possible improvements rather than impairments in EF/academic outcomes. Given these scale differences, future analyses should consider defining substance use as low *or* moderate (instead of low-to-moderate) to see if significant relationships exist based on these two narrower definitions of use.

An additional complicating factor in the ABCD Study is the length of time between conception/pregnancy and data collection. Most of the data collected on maternal substance use during pregnancy was obtained at least nine years after the child was born (perhaps 10 years since the child was conceived), meaning the parent/guardian was reporting information from 10-year-old memories of substance use, making this information less reliable than it would have been had it been collected during pregnancy and corroborated by additional testing (with the mother's consent). Further research is needed to establish more effective data collection techniques associated with low-to-moderate prenatal alcohol and/or tobacco use if we are to understand the potential effects of this level of substance use on children and adolescents, particularly in terms of their cognitive functioning and academic outcomes.

Of course, a significant limitation of this study is the correlational nature of the data. Findings presented in this paper reflect *associations* between prenatal exposure and various outcomes, and these relationships cannot reveal if there is a causal connection between these variables.

4.5. Conclusions

In conclusion, the current study explored the relationships between low-to-moderate prenatal alcohol and/or tobacco exposure and adolescents' subsequent EF and academic performance at two separate time points in their development, using data from the ABCD Study. Although there were no significant findings related to low-to-moderate alcohol or tobacco use, there were significant findings associated with substance use when including data from participants who consumed *greater* than low-to-moderate amounts of these substances, and there were also significant effects associated with combined use of these two substances. In the face of these inconclusive findings, the safest recommendation for the public continues to be to avoid alcohol and tobacco throughout pregnancy. Given the longitudinal scope of the ABCD Study, re-visiting these adolescents as they move through their teenage years and emerge into young adulthood, may reveal relationships between their prenatal substance exposure and subsequent cognitive and academic outcomes; relationships that were not apparent when examining the baseline and 2-year follow-up data.

An important aspect of this study explored EF from two theoretical perspectives [i.e., developmental psychology research (EF-Broad) and cognitive psychology research (EF-Narrow)]. Analyses from these two perspectives yielded a recurring finding related to the importance of WM, specifically as an effective predictor of academic performance. By deconstructing EF, this study offered a novel approach to exploring the cognitive abilities measured in the ABCD Study and has provided new insights into the connection between WM, EF, academic performance, and prenatal teratogen exposure.

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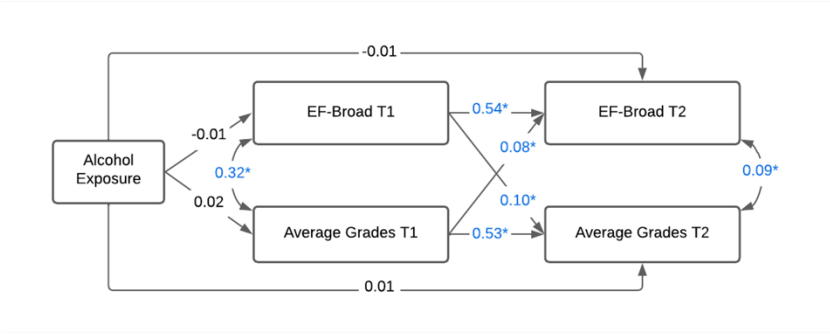
Appendix

Low-to-Moderate (L2M) and Full Sample Dataset Path Model Figures

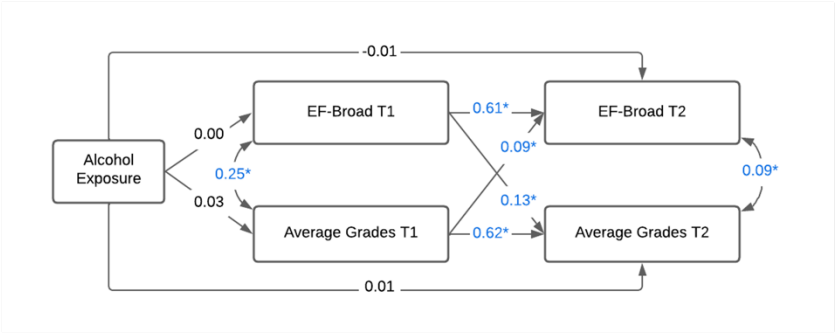
Figure 29

L2M Alcohol Use Models 1-4

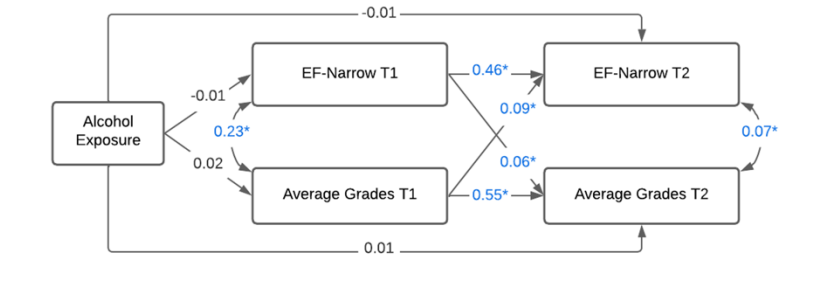
Model 1. L2M Simple: Alcohol Use, EF-Broad T1/T2, Average Grades T1/T2



Model 2. L2M Simple + Demographics: Alcohol Use, EF-Broad T1/T2, Average Grades T1/T2



Model 3. L2M Simple: Alcohol Use, EF-Narrow T1/T2, Average Grades T1/T2



Model 4. L2M Simple + Demographics: Alcohol Use, EF-Narrow T1/T2, Average Grades T1/T2

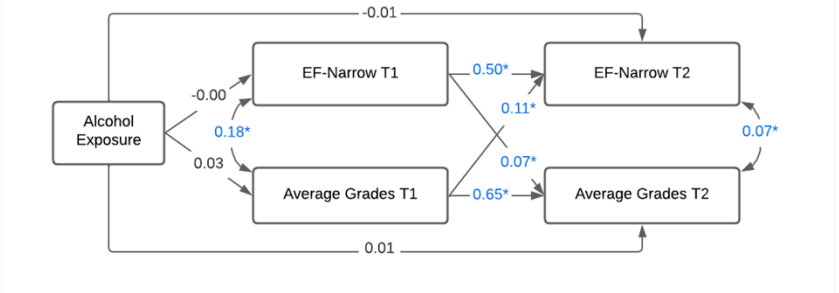
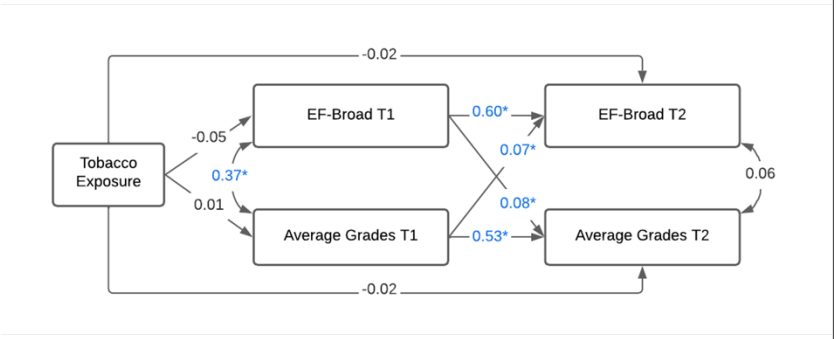


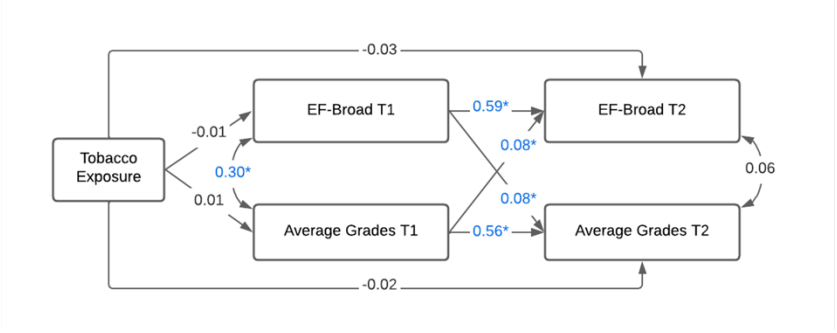
Figure 30

L2M Tobacco Use Models 5-8

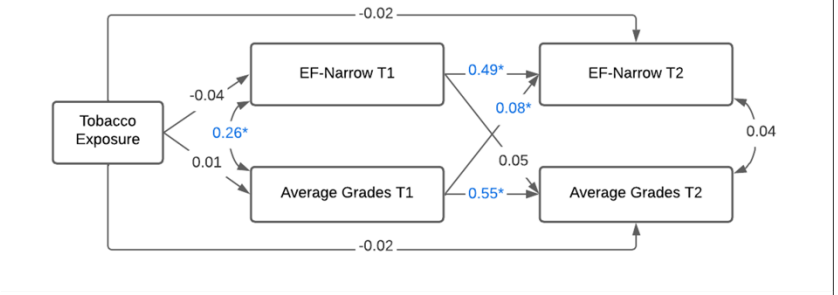
Model 5. L2M Simple: Tobacco Use, EF-Broad T1/T2, Average Grades T1/T2



Model 6. L2M Simple + Demographics: Tobacco Use, EF-Broad T1/T2, Average Grades T1/T2



Model 7. L2M Simple: Tobacco Use, EF-Narrow T1/T2, Average Grades T1/T2



Model 8. L2M Simple + Demographics: Tobacco Use, EF-Narrow T1/T2, Average Grades T1/T2

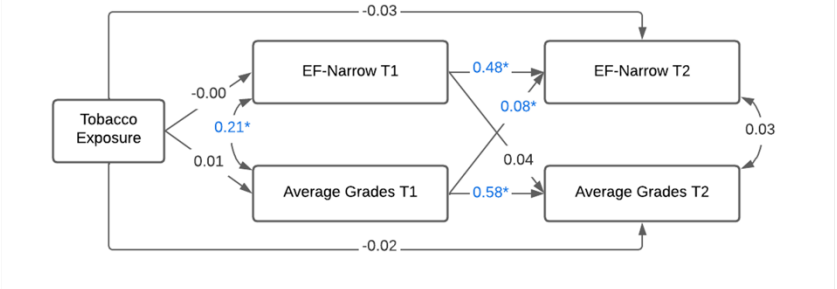
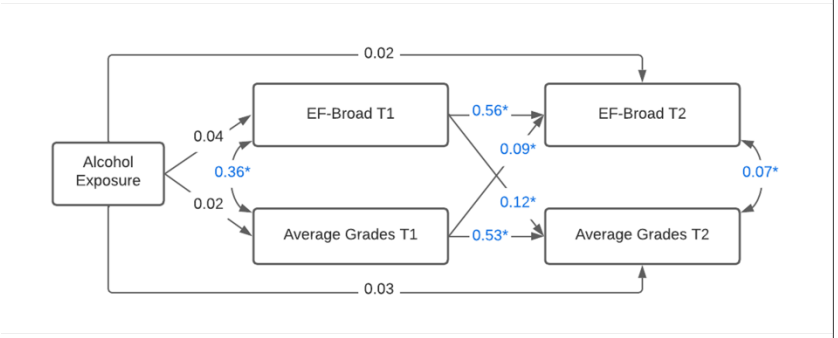


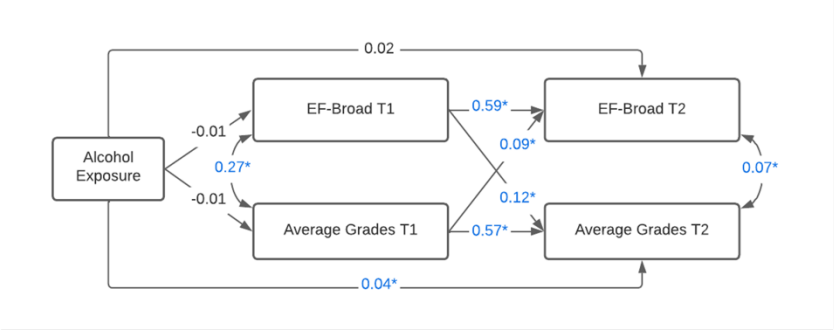
Figure 31

Full Sample Dataset Alcohol Use Models 9-12

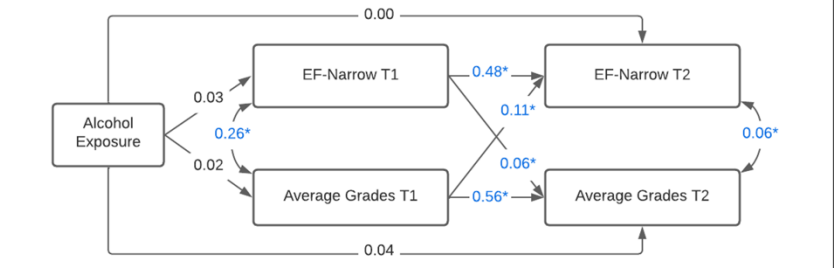
Model 9. Full Simple: Alcohol Use, EF-Broad T1/T2, Average Grades T1/T2



Model 10. Full Simple + Demographics: Alcohol Use, EF-Broad T1/T2, Average Grades T1/T2



Model 11. Full Simple: Alcohol Use, EF-Narrow T1/T2, Average Grades T1/T2



Model 12. Full Simple + Demographics: Alcohol Use, EF-Narrow T1/T2, Average Grades T1/T2

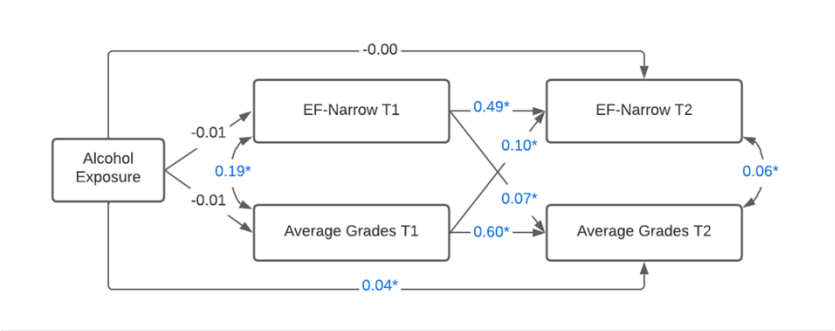
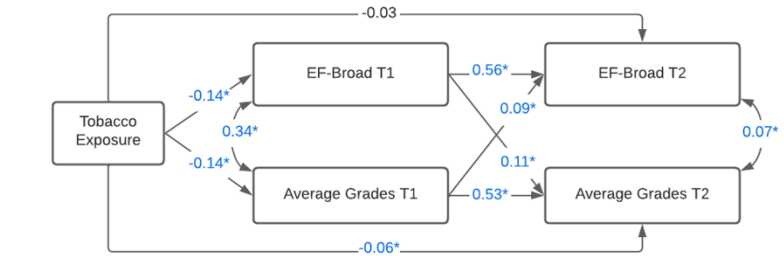


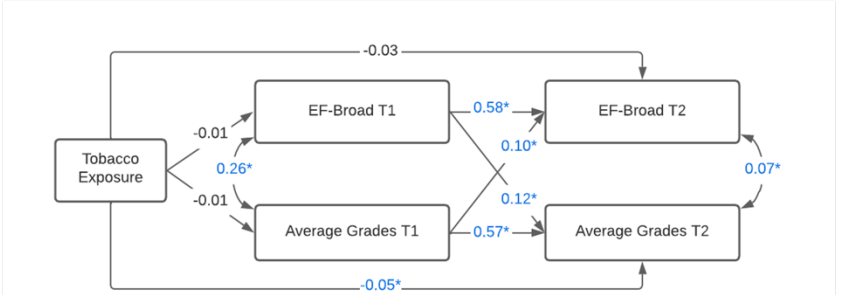
Figure 32

Full Sample Dataset Tobacco Use Models 13-16

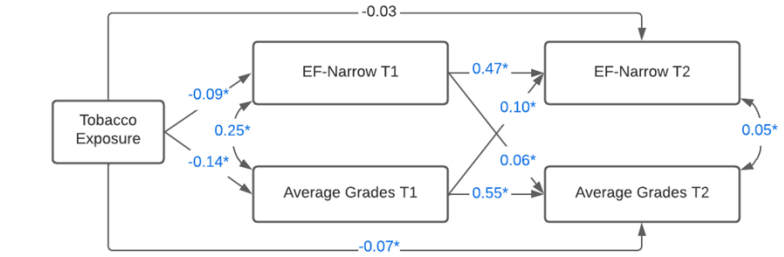
Model 13. Full Simple: Tobacco Use, EF-Broad T1/T2, Average Grades T1/T2



Model 14. Full Simple + Demographics: Tobacco Use, EF-Broad T1/T2, Average Grades T1/T2



Model 15. Full Simple: Tobacco Use, EF-Narrow T1/T2, Average Grades T1/T2



Model 16. Full Simple + Demographics: Tobacco Use, EF-Narrow T1/T2, Average Grades T1/T2

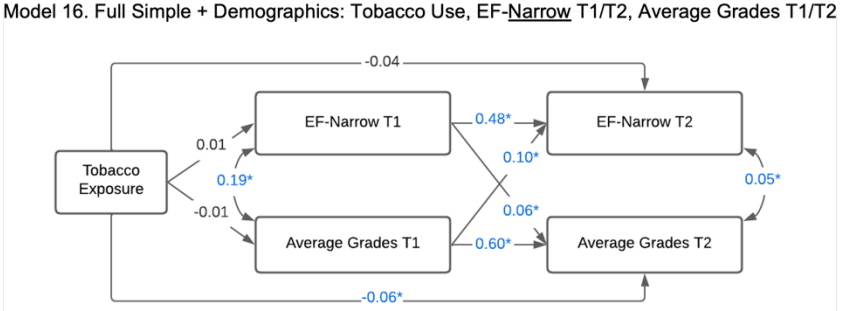
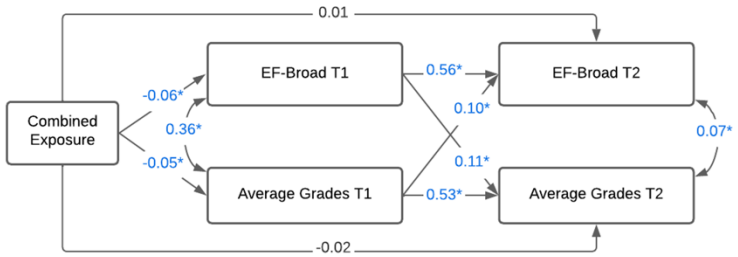


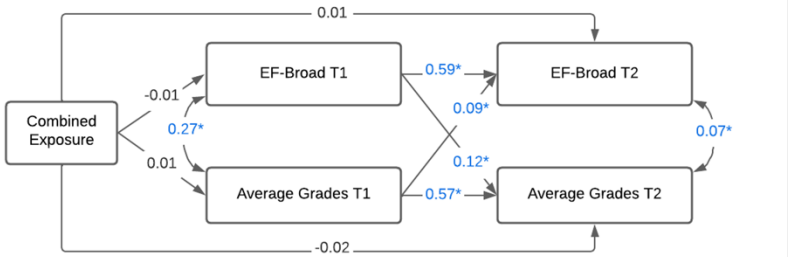
Figure 33

Full Sample Dataset Combined Use Models 17-20

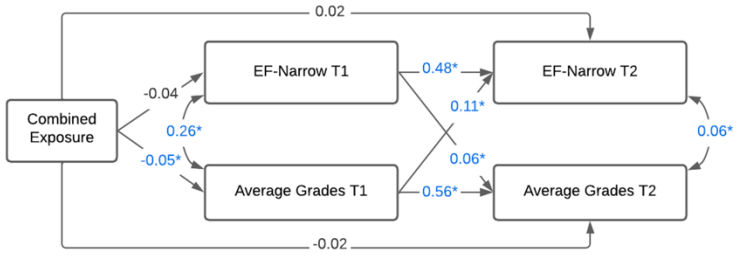
Model 17. Full Simple: Combined Use, EF-Broad T1/T2, Average Grades T1/T2



Model 18. Full Simple + Demographics: Combined Use, EF-Broad T1/T2, Average Grades T1/T2



Model 19. Full Simple: Combined Use, EF-Narrow T1/T2, Average Grades T1/T2



Model 20. Full Simple + Demographics: Combined Use, EF-Narrow T1/T2, Average Grades T1/T2