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Sex differences in Piaget's Water Level Tasks:
A multiverse meta-analysis

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Abstract

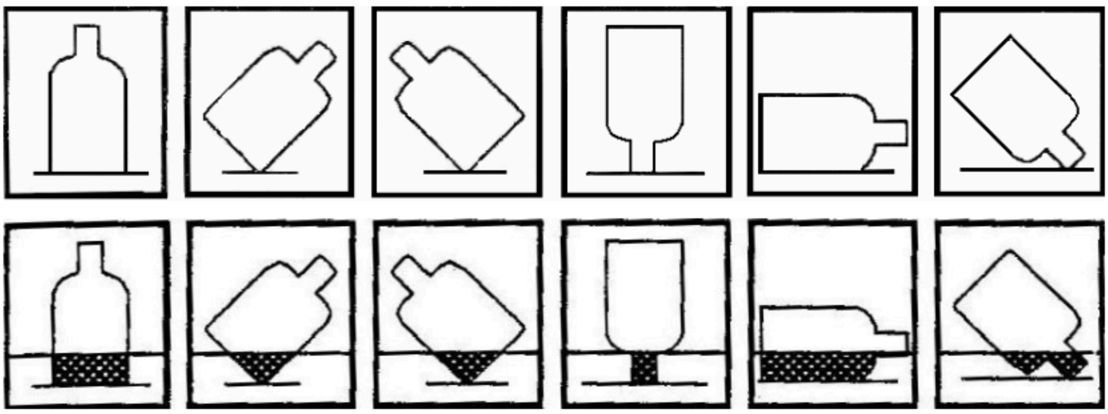
Nearly 80 years ago, Jean Piaget introduced the Water Level Task (WLT) to investigate emerging concepts of horizontality invariance in children, proposing that a universal ability to solve this task by about age nine reflects the progression through the concrete operational stage of cognitive development. However, subsequent research has shown substantial difficulties in solving WLTs even among adults, with men consistently outperforming women. While this sex difference has repeatedly been replicated, its generality and cross-temporal stability remain unclear. To address this gap, the present research synthesized all available evidence of sex differences in WLT performance from 1964 to 2025 (267 samples, totaling more than 38,000 participants) by means of preregistered random-effects meta-analyses. The stability of the meta-analytical summary effect across potential moderators was examined using subgroup analyses and precision-weighted meta-regressions. Moreover, meta-analytical specification curve analyses and a combinatorial meta-analysis were conducted to account for all reasonable and possible ways of which data to meta-analyze and how to meta-analyze them. Results showed moderately sized sex differences in WLT performance favoring men ($d = 0.50$; 95% CI [0.47, 0.54]) that increased with age but declined slightly over time. Multiverse analyses revealed remarkable generality of this effect across different sample characteristics, test variants, and meta-analytical decisions, with 12,276 out of 12,996 summary effect calculations (94%) yielding nominally significant male advantages, averaging $d = 0.49$. Taken together, these findings indicate moderate, robust, yet cross-temporally diminishing sex differences in WLT performance, challenging Piaget's notion of a universal understanding of horizontality invariance by late childhood.

Keywords: Water Level Task, Piaget, sex differences, meta-analysis, multiverse meta-analysis, specification curve, combinatorial meta-analysis.

Introduction

In their book *The Child's Conception of Space*, Jean Piaget and Bärbel Inhelder (1948/1956) described the results of a series of experiments they conducted to examine the development of various spatial concepts in children. This work included the concept of horizontality invariance, i.e., the understanding that the surface of liquids invariantly remains horizontal. To investigate the emergence of horizontality invariance, they introduced the so-called Water Level Tasks (WLTs), which require drawing the water surface into empty tilted containers (see Fig. 1). Based on their results, Piaget and Inhelder (1948/1956) suggested the progressive development of a stable external reference frame, an overall coordinate system, resulting in the immediate prediction of the invariant horizontal from about age nine. Therefore, under their assumption of a universal stage structure, every typically developing individual older than that age should be able to solve WLTs correctly.

Figure 1. *Illustration of the Piagetian Water Level Tasks.*



Note. Example items (above) to illustrate the original WLT designed by Piaget and Inhelder (1948/1956) and the correct solutions (below). Figure adapted from Ackermann (1991).

However, sixteen years after the publication of this initial work, it was shown that even adults show considerable difficulties solving these seemingly simple tasks (Rebelsky, 1964). Further, sex differences favoring male participants were found, indicating that women showed larger difficulties solving WLTs than men. Over the following six decades, these sex differences were repeatedly replicated across different age groups, using several variations of the original test design (e.g., Liben, 1974; McNeal et al., 2024; Nordvic & Amponsah, 1998; Tran & Formann, 2008). Whereas initial meta-analytic evidence indicated medium-sized sex differences with male advantages (Pietschnig & Voracek, 2011; Voyer et al., 1995), little is known about the generalizability of this effect across time as well as different test versions, samples and meta-analytical models. The present research aims to fill this gap by examining cross-temporal trends and by conducting specification curve and multiverse meta-analyses.

Situating Emerging Horizontality Invariance in Piagetian Stage Theory

The Stages of Cognitive Development

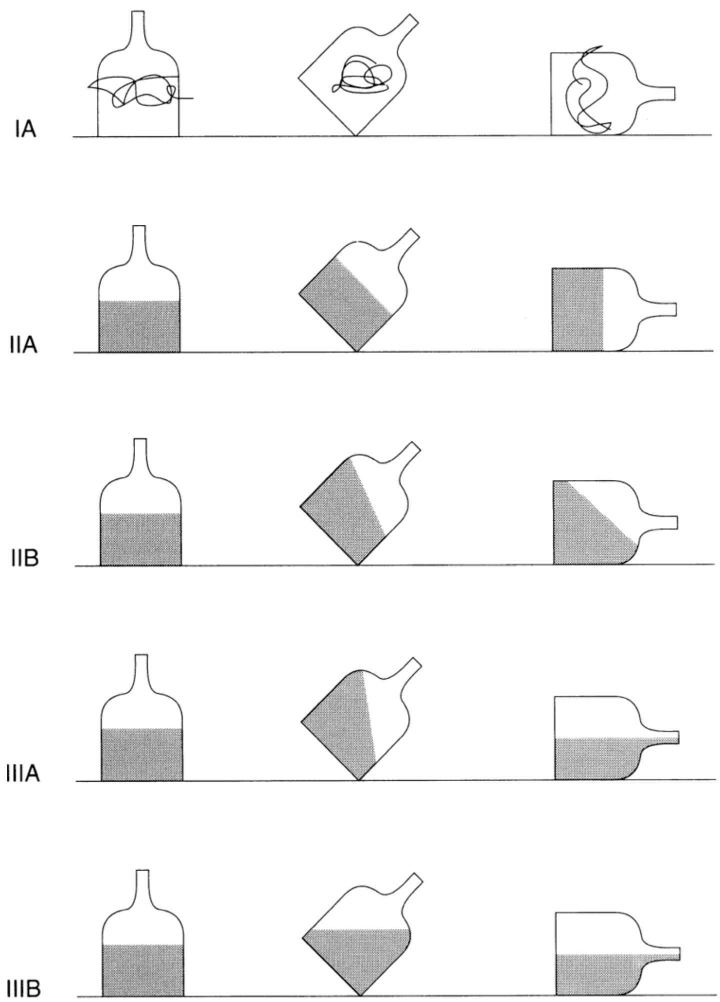
Jean Piaget introduced his stage theory of cognitive development in the early 20th century, according to which every normally developing child progresses through four key stages as their general system of thought evolves. He believed that this gradual development follows an invariant hierarchical sequence, as the stages build on each other and are characterized by a more complex understanding of the world compared to their precursor (Bidell & Fisher, 1992; Chapman, 1988; Müller et al., 2015; Piaget, 1962). The sensorimotor stage lasts from birth to 2 years of age and is characterized by perception-action cycles, through which infants interact with their environment and thus learn to distinguish between the self, other people, and the outside world (Piaget, 1936/1952, 1937/1954). During the pre-operational stage, which lasts from about 2 to 7 years, children begin to use symbolic thought, imagination, and language. However, thinking remains egocentric and lacks an understanding of the transformation of reality, i.e., operation (Piaget, 1962; Piaget & Inhelder, 1966/1969). In the concrete operational stage, which lasts from about 7 to 11 years, children learn to logically solve problems that apply to specific (i.e., concrete) events or objects (Piaget, 1941/1965). It is only in the final, formal operational stage of intellectual development, which begins around age 11 to 12, that adolescents become capable of abstract and hypothetical thinking (Inhelder & Piaget, 1955/1958).

Horizontality Invariance: A Concrete Operational Concept

Based on their empirical work on emerging spatial concepts in children, Piaget and Inhelder (1948/1956) described the development from notions of topological (e.g., proximity, separation, order, and enclosure) to projective (e.g., alignment, relations between objects, and perspectives from different viewpoints) and Euclidean (e.g., angles, conservation of distances and lengths, and parallelism) spatial concepts. In the course of the transition from a projective to a Euclidean understanding of space, an external frame of reference, a so-called coordinate system required for representing orientation and movement of objects in space, gradually develops during the late concrete operational stage. Consequently, the ability to rely on this external reference frame is considered an indicator of the complete organization of concrete operational thought.

Focusing on the horizontal axis of this coordinate system, the Water Level Task was designed by Piaget and Inhelder (1948/1956) to investigate the concept of horizontality invariance, meaning the ability to understand the constancy of the surface of a liquid regardless of the container's position. To test this concept, a series of empty vessels tilted at various angles was shown to a group of children and adolescents. They were then instructed to imagine the containers to be half filled with liquid and to draw its surface where they would expect it to be. Based on the participants' answers, a hierarchical sequence of development was suggested, including three main stages and several substages (see Fig. 2).

Figure 2. *Stages of WLT Responding Behavior Proposed by Piaget and Inhelder (1948/1956).*



Note. Figure from Vasta and Liben (1996).

According to Piaget and Inhelder (1948/1956), Stage I extends to approximately 4 years of age and is characterized by children's failure to recognize the water surface as a line. Instead, the liquid is depicted as a mass within the container, which is attributed to a purely topological conception of fluids at this age. In Stage II, which is divided into two substages and lasts from about 4 to 6 years, children identify the water level as a straight line but use the outline of the vessel (i.e., the internal reference frame) rather than the table depicted beneath the container (i.e., the external reference frame) as an orientation. In Substage IIA, children mostly draw the water surface parallel to the base of the container. In Substage IIB, they expect the water level to tilt along with the vessel and therefore tend to draw the water level at an angle towards the opening. In a transitional Stage between IIB and IIIA, children recognize horizontality invariance only in orthogonal positions, supposedly due to an emerging association with an external reference system. Over the course of stage III, an understanding of horizontality invariance is gradually established. Substage IIIA lasts approximately from 7 until 9 years and thus coincides with the beginning of the concrete operational stage. Children in this substage reach the correct response using a trial-and-error approach, which is generally considered an important way of constructing operational systems. Finally, "about the age of 9, Substage IIIB begins with the immediate prediction of [the invariant] horizontal […] as part of an overall system of co-ordinates" (Piaget & Inhelder, 1948/1956, p. 384). It is concluded that, from about this age, the horizontality principle is directly applied to all situations due to complete organization of operational thought. This implies that every typically developing person older than about 9 years should be able to solve WLTs correctly. However, research conducted in the following decades contradicted this claim.

Sex Differences in (Adult) WLT Performance

The initial publication of the WLTs among many other spatial tasks described in *The Child's Conception of Space* (Piaget & Inhelder, 1948/1956) was followed by a substantial body of research attempting to replicate the observed stages of spatial development (Liben, 1991b). For example, in a subsequent investigation, the WLT was administered to 194 children and adolescents (Dodwell, 1963). Although the general order of the postulated stages was broadly supported, the well-defined transitions between developmental stages could not be replicated. Specifically, the majority of participants could not be assigned unambiguously to a single stage but were classified into a mixed category, exhibiting response behaviors characteristic of multiple stages within the same individual. Moreover, the age limits reported in the original study could not be clearly identified.

In the mid 1960s, Freda Rebelsky (1964) was the first to administer a WLT to an adult sample of 126 psychology undergraduates aged 20 to 26 years. Surprisingly, results indicated that more than half of the participants erred by more than 5 degrees from the true horizontal across all four tilted test items. This performance pattern challenged the prevailing assumption that the invariant horizontal could be predicted without error once concrete operational thought was fully organized from around nine years of age. In addition, results revealed a small sex difference favoring men, indicating that women produced more errors. These novel findings marked the beginning of a large body of research that repeatedly demonstrated sex differences with male advantages in WLT performance.

While some studies adopted research designs closely aligned with the one employed in the first adult WLT study (e.g., Liben & Golbeck, 1986; Mowrer-Popiel & DeLisi, 1984), many subsequent studies replicated the sex differences using various adaptations of the WLT. For example, considerable variability emerged in the number of WLT items administered. Some studies only administered a single WLT item (e.g., Cashdan et al., 2012; Hecht & Proffitt, 1995; Robert & Chaperon, 1989), many studies involved six to eight (e.g., Amponsah, 2000; Christensen, 2011; Ecuyer-Dab & Robert, 2004; Kalichman, 1986; Rebelsky, 1964; Sorby et al., 2019; Thomas & Lohaus, 1993) or up to 20 items (e.g., Doyle et al., 2012; Harris et al., 1977; Krasnoff & Walker, 1983; Meneghetti et al., 2021; Wegesin, 1995, 1998), and some administered large pools of more than 200 items (Rilea, 2008; Robert & Berthiaume, 2002). Similarly, stimulus characteristics varied substantially across studies. While many investigations used rectangular vessels consistent with the original task format (e.g., Hill, 2004; Liben, 1974; Lohaus et al., 1996; Robert & Berthiaume, 2002), other WLT versions included alternative stimulus shapes, such as Florence flasks (e.g., Geiringer, 1976; Tran & Formann, 2008; Weixelbraun, 2009), curved bottles (e.g., Berenbaum et al., 2012; Murphy-Berman, 1986; Sholl & Liben, 1995), and jars (e.g., Alexander, 2005; Farace, 1996; Kelly & Beltz, 2022). Many studies provided a horizontal cue below the stimuli presented (e.g., Bracken et al., 2024; Cherney et al., 2008; Sholl & Liben, 1995; Weisberg et al., 2014), while others did not (e.g., Jansen-Osmann et al., 2008; Liben, 1991a; Polifka et al., 2023; Robert & Héroux, 2004). Moreover, whereas most studies used the original response format of drawing the water line (e.g., Abravanel & Gringold, 1977; Kalichman, 1986; Merrill et al., 2016; Merriwether & Liben, 1997; Voyer & Sullivan, 2003), others employed multiple choice formats (e.g., Harris et al., 1977; Lawton, 1994; Morra, 2008; Rahe & Jansen, 2022), and some required participants to respond by adjusting a model of the water level (Geiringer, 1976; Thomas & Jamison, 1975; Thomas & Lohaus, 1993) or the vessel (e.g., Richa, 1990).

Finally, while many studies maintained the original paper and pencil format (e.g., Kenyon, 1984; Morris, 1971; Seng & Tan, 2002; Sholl & Liben, 1995; Tomai et al., 2024), many newer studies administered digital versions on computers (e.g., Lucas & Alwens, 2000; Reilly et al., 2016; Signotella & Liben, 2024) or smartphones (Bracken et al., 2024; Rahe & Jansen, 2022; Polifka et al., 2023).

Across the wide variety of WLT adaptations, sex differences with male advantages have been found in children (e.g., Merril et al., 2016; Seng & Tan, 2002; Thomas & Lohaus, 1993), adolescents (e.g., Amponsah, 2000; Lohaus et al., 1996; Sorby et al., 2019), and adults (e.g. Morris, 1971; Tomai et al., 2024; Voyer & Sullivan, 2003). Much of this research situated these findings within broader discussions of sex differences in spatial abilities. A better understanding of what performance on WLTs reflects in terms of spatial cognition requires embedding the task within broader theoretical frameworks of intelligence as well as established categorizations of spatial ability.

Defining Spatial Ability

The ability to represent and process spatial information encompasses a broad set of skills, including mental encoding and manipulation of shapes, positions, movements, and relations within and between entities (Newcombe & Shipley, 2015; Uttal et al., 2024). Despite its importance for everyday activities such as finding the from one pace to another or catching a ball, no comprehensive framework of spatial ability and its subcomponents has yet been established (Hegarty & Waller, 2005; Uttal et al., 2013, 2024).

Conceptual Development of Spatial Ability as a Factor of Human Intelligence

Spatial cognition first emerged as a component of human intelligence in early theoretical frameworks (Buckley et al., 2018), which are central to understanding how conceptions of spatial ability have evolved over time.

Initial Defining Approaches. The idea of spatial ability was originally conceived by Galton (1879, 1880) as part of his work on mental imagery and was further refined by subsequent conceptions of intelligence. While Spearman (1904, 1927) posited a two-factor theory involving a single *g*-factor alongside task-specific abilities, Thorndike (1920, 1921) challenged this notion by proposing three intelligences (abstract, mechanical, and social). Thorndike included spatial ability in the concept of mechanical intelligence, described as the ability to understand and manage (relations among) physical objects, only implicitly (Mohler, 2008). Thurstone (1938), in turn, explicitly included the factor *Space*, i.e., the perception, understanding, and visualization of spatial relations, in his factor-analytic model of primary mental abilities.

Hierarchical Models of Intelligence. Following Spearman, Thorndike, and Thurstone, subsequent factor-analytical intelligence models postulated hierarchical structures. Vernon (1950, 1961) proposed a four-level structure with psychometric *g* on the highest level, followed by two major group factors, namely the verbal-educational (v:ed) and the kinesthetic-motor (k:m) group. These are further divided into partly interlinked minor group factors, which are composed of several specific factors. Spatial abilities are thereby a minor group factor within the k:m complex, which Vernon also referred to as the spatial-practical-mechanical group (Vernon, 1965).

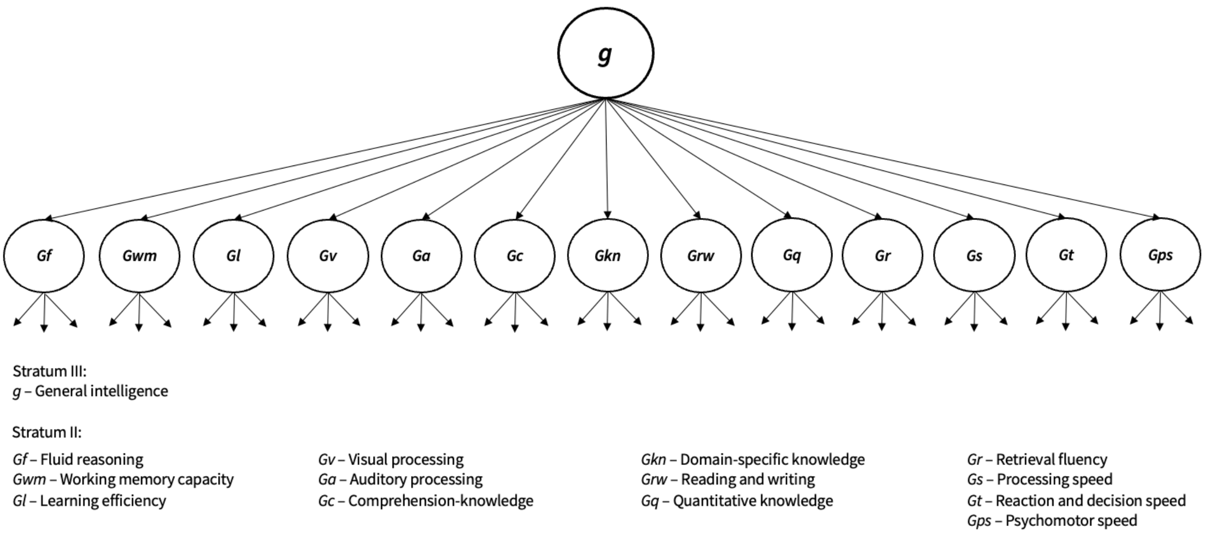
Cattell (1943) postulated two distinct but correlated types of intelligence subordinate to an overarching *g*-factor in his *Gf*-*Gc* theory. Fluid intelligence (*Gf*) refers to the ability to adapt to new problems or situations without requiring substantial prior experience, while crystallized intelligence (*Gc*) encompasses the accumulated knowledge and skills acquired over a lifetime. Whereas spatial abilities are not directly mentioned in Cattell's model, they are required for solving tests of fluid intelligence (Cattell & Horn, 1978). The *G*f-*G*c theory was extended by his student Horn (1965, 1991) based on further empirical work neuropsychological and factor-analysis. This led to the identification of seven additional factors, namely quantitative reasoning (*Gq*), short-term apprehension-retention (*Gsm*), fluency of retrieval from long-term storage (*Glr*), visual processing (*Gv*), auditory processing (*Ga*), processing speed (*Gs*), and correct decision speed (CDS). Spatial reasoning is subsumed under *Gv*, as it is measured by tasks requiring visual constancy, closure, and fluency in the perception and mental manipulation of objects in space (Horn & Blankson, 2005).

Based on his extensive reanalysis of more than 450 datasets that had been used to develop the common models of intelligence, Carroll (1993) proposed a hierarchical structure with three levels. The most general level (stratum III) involved psychometric *g*. Eight stratum II factors were identified as hierarchically subordinate and closely corresponded to the secondary factors identified by Cattell and Horn (see Schneider & McGrew, 2018, for a comparison). At the lowest level (stratum I), narrowly defined abilities load onto strata II and III. Spatial and other visual perceptual skills are subsumed under the stratum II factor *Broad Visual Perception*, described as abilities to recognize, mentally represent, and mentally manipulate forms, shapes, and positions of visually perceived objects. Five stratum I abilities were identified as subordinate to this factor, namely visualization (VZ), spatial relations (SR), closure speed (CS), flexibility of closure (CF), and perceptual speed (P).

A synthesis of the *Gf-Gc* theory and the three-stratum model resulted in the Cattell-Horn-Carroll (CHC) theory (McGrew, 1997; Schneider & McGrew, 2012), currently recognized as the most comprehensive and empirically supported intelligence model (Agelink van Rentergem et al., 2020; Schneider & McGrew, 2018).

Visuospatial Abilities in the CHC Theory. Initially introduced by McGrew (1997) in an effort to integrate the approaches of Cattell, Horn, and Caroll to a single taxonomy, the CHC theory is a dynamic model continuously refined based on current research (Schneider & McGrew, 2012). The most recent version proposes a hierarchical framework organized according to three levels (see Fig. 3) with psychometric *g* at the top (stratum III), 13 non-tentative along with five tentative broad abilities (stratum II) and more than 80 narrow abilities. The broad and narrow abilities are distinct but positively intercorrelated and constitute an integrated system of problem solving. At the bottom of the hierarchy are narrow abilities that are defined by individual test features (Schneider & McGrew, 2013, 2018).

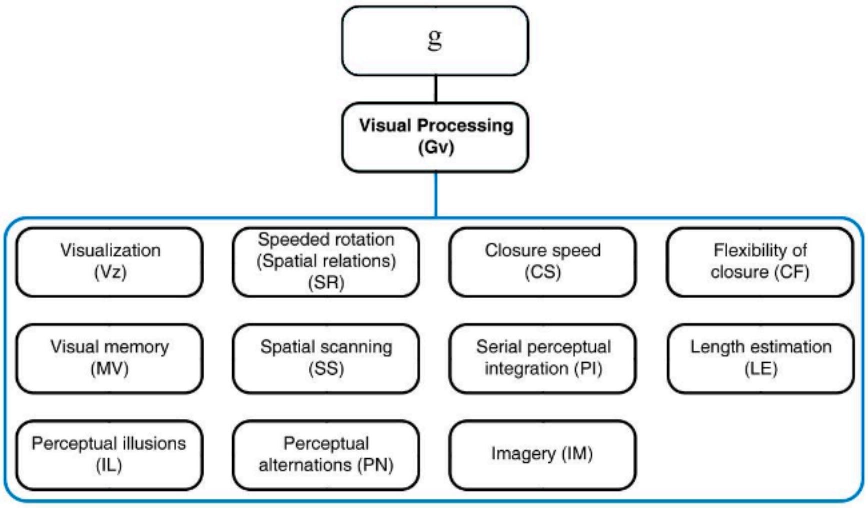
Figure 3. *The Cattell-Horn-Cattell Theory of Intelligence.*



Note. The figure includes 13 non-tentative broad abilities. In the most recent version of the CHC theory, five tentative broad abilities are proposed (see Schneider & McGrew, 2018, for an overview).

Spatial skills are represented in the CHC model as the second-order *Visual Processing* (Gv) factor, elsewhere referred as visual-spatial thinking (Floyd et al., 2003) or spatial ability (Buckley et al., 2018). Gv is described as the ability to use mental imagery to solve problems (Schneider & McGrew, 2012). It involves perceiving and transforming visual objects, processing them mentally, and maintaining spatial orientation as they change or move through space (Schneider & McGrew, 2018). In total, 11 narrow abilities load on visual processing (see Fig. 4 for an overview and Schneider et al., 2013 for a detailed description of the stratum I factors). These first-order factors were further grouped into spatial skills involving the ability to mentally manipulate objects (e.g., visualization, speeded rotation), perceptual factors referring to the ability to perceive visuo-spatial information (e.g., perceptual alternations, spatial scanning), and a memory factor, which include storing mental representations of such information (i.e., visual memory) (Buckley et al., 2018).

Figure 4. *Factor Structure of Visual Processing Within the CHC Theory.*



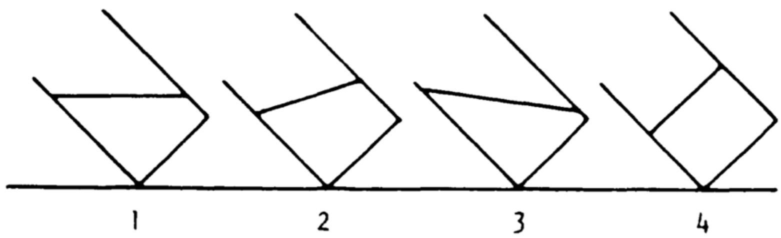
Note. Hierarchically subordinate to psychometric *g* (stratum III), visual processing (*Gv*) is one of 11 broad abilities (stratum II), which is further subdivided into 11 narrow abilities (stratum I). Figure from Buckley (2018).

Although the CHC theory represents a largely comprehensive integration of several previous approaches to the classification of cognitive abilities, it may not provide an entirely cohesive account of the structure of spatial ability. In particular, dynamic as opposed to static aspects of spatial processing as well as factors dissociable from those identified within the theory, such as mental rotation and spatial orientation, are currently underrepresented in the CHC framework (Buckley et al., 2018; Hegarty & Waller, 2005). Moreover, factor-analytic approaches may overlook certain components of spatial intellect, as the tests commonly used to assess spatial skills may not capture the full range of spatial functioning (Uttal et al., 2024). Meanwhile, some spatial tests, including WLTs, cannot be clearly assigned to one single narrow ability (Uttal et al., 2013). Therefore, to obtain a comprehensive understanding of spatial ability and of how WLTs measure spatial skills, it is useful to consider the traditional, bottom-up psychometric approaches in combination with theoretically and empirically driven top-down frameworks (Buckley et al., 2013; Newcombe & Shipley, 2014).

Theoretically Driven Categorizations of Spatial Ability

Linn and Petersen (1985) addressed the limitations of test-specificity of factor-analytical models and proposed a theoretically grounded, general structure of spatial ability. Drawing on research examining cognitive processes involved in solving spatial tasks, they distinguished between three broad categories, namely mental rotation, spatial visualization, and spatial perception. Mental rotation involves the ability to imaginatively rotate two- or three-dimensional objects and can be assessed using measures such as the Mental Rotation Task (MRT; Shepard & Metzler, 1971) or "Cubes" in the Primary Mental Abilities test battery (Thurstone & Thurstone, 1941). Spatial visualization is described as the ability to mentally perform complex, multistep manipulations of spatial information and can be measured with tasks including the Embedded Figures Test (EFT; Witkin, 1971) and the Paper Folding Test (PFT; Ekstrom et al., 1976). Spatial perception involves the ability to determine spatial relationships with respect to the orientation of one's own body, despite distracting information and is commonly assessed with tasks such as the Rod-and-Frame-Test (RFT; Witkin et al., 1962) and the WLT (see Fig. 5 for the example item provided by Linn & Petersen, 1985).

Figure 5. *Multiple Choice WLT Item.*

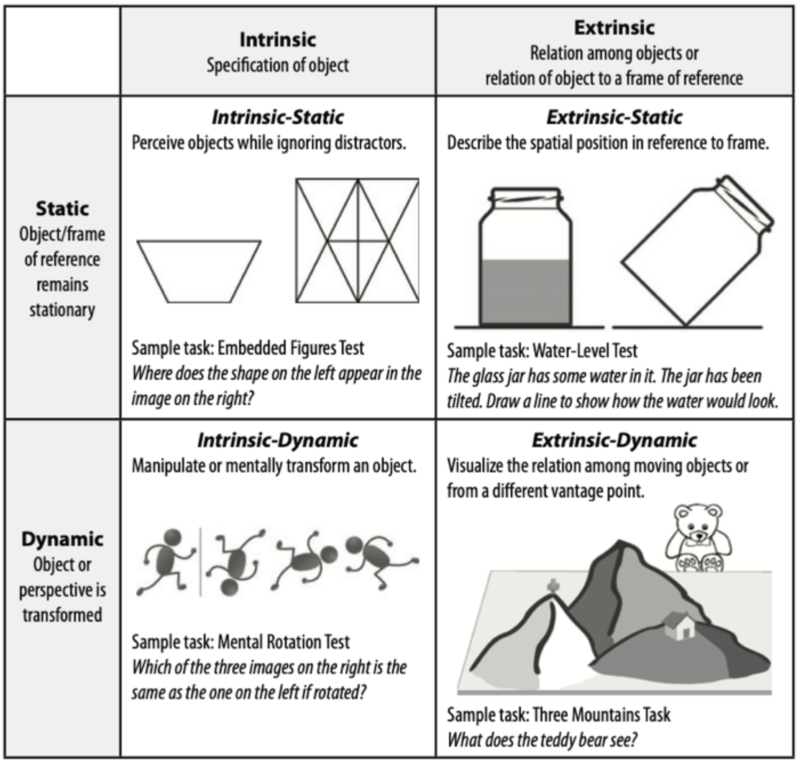


Note. The figure shows a MC variant of the WLT, in which participants are asked to indicate the correct depiction of water in a tilted vessel. Figure from Linn and Petersen (1985).

This categorization was later criticized as "somewhat arbitrary" (Voyer et al., 1995, p. 252). The definitions, particularly of the spatial visualization component, were considered vague, as several tests classified in this grouping contained aspects of the other two components. For example, the Identical Blocks Test (Stafford, 1961) was classified as a measure of spatial visualization although it heavily relies on mental rotation (Voyer et al., 1995). Despite such objections, the three-fold classification was adopted in numerous subsequent studies and is still used as a theoretical framework to conceptualize spatial skills in contemporary work (e.g., Black, 2005; Voyer & Jansen, 2017; Zach & King, 2022).

Newcombe and Shipley (2014) introduced a refined approach based on linguistic and neuroscientific research. In their two-dimensional framework of spatial skills, they distinguish between intrinsic (i.e., relations within an object) and extrinsic (i.e., relations between different objects) as well as static (i.e., to be perceived statically) and dynamic (i.e., to be transformed dynamically) spatial information. This yielded a 2 x 2 classification with four broad categories of spatial skills (see Fig. 6). The intrinsic-static category refers to the perception of spatial configurations of objects. The intrinsic-dynamic category requires visualization and mental alteration of objects. The extrinsic-static category includes the comprehension of abstract spatial principles such as horizontality invariance. Finally, the extrinsic-dynamic category encompasses maintaining a stable representation of an environment as one of its objects or the viewer moves (Newcombe & Shipley, 2014; Uttal et al., 2013). This classification has been used as a theoretical foundation in many recent research projects on spatial cognition (e.g., Gilligan et al., 2017; Lasc et al., 2025; Xie et al., 2020)

Figure 6. *2 x 2 Classification of Spatial Reasoning.*

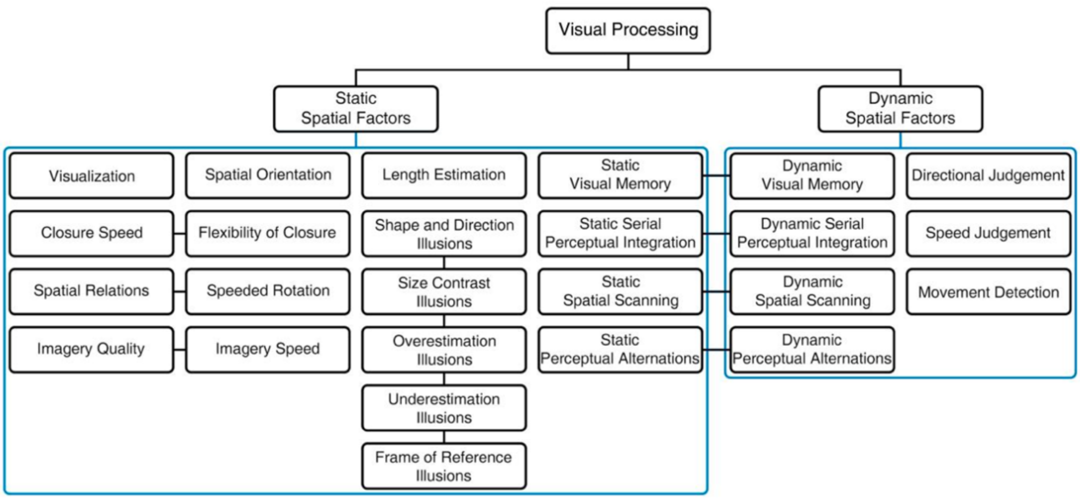


Note. Figure from Okamoto et al. (2015).

An Integration of Bottom-Up and Top-Down Approaches

Buckley et al. (2018) conducted a review and synthesis of defining approaches and empirical evidence on spatial factors to provide an up to date, comprehensive and empirically based framework of spatial cognition. They suggest an extension of the 11 broad spatial abilities postulated in the current version of the CHC theory to 25 unique first-order factors associated with spatial ability, grouped into static and dynamic categories as suggested by Newcombe and Shipley (2014; see Fig. 7). Within the static category, Buckley et al. proposed to split the *Perceptual Illusions* factor from the CHC theory into five separate factors that involve the ability to not be fooled when perceiving different types of visual information. One of these factors is *Frame of reference illusions*, which involves the comparison of an object to a reference frame and can be assessed using tasks such as the Rod-and-Frame-Test. Although not mentioned explicitly by Buckley et al. (2018), the WLT may serve as a measure of this category, as has been done in previous research (e.g., McNeal et al., 2024).

Figure 7. *Spatial Factor Framework of Presented by Buckley et al. (2018).*



Note. Figure from Buckley (2018).

Taken together, the different defining approaches illustrate that spatial ability is not a single, unified construct but rather a constellation of distinct yet related skills. Despite differences in terminology and scope, most models converge on the view that spatial perception, or closely related constructs, represents a fundamental dimension of spatial ability.

Within this context, WLTs have been widely applied as measures of spatial perception (e.g., Bower & Liben, 2023; Cashdan et al., 2012; Goldsmith et al., 2016; Morawietz et al., 2024a, 2024b, 2024c; Nordvik & Amponsah, 1998; Signorella et al., 1989). Moreover, WLTs have been used to operationalize a range of broader or more narrowly defined constructs, including cognitive level (Fenderson, 1985), spatial ability (McJunkin, 1991), visuospatial construction (Dessens et al., 2000), spatial visualization (Sorby et al., 2019), intuitive physics (Abadi et al., 2023; Riener et al., 2005), field independence (Bialystok, 1992; Van Esch, 1978), implicit concepts of gravity (Pulos et al., 1997; Weseman et al., 2025), and horizontality concepts (Kalichman, 1986; Liben & Golbeck, 1980; McAfee & Proffitt, 1991).

Despite substantial variability in how WLTs have been conceptualized and operationalized across studies, WLTs can be situated consistently within most theoretical frameworks discussed above as measures of the perceptual component of spatial cognition. Specifically, they have been classified as measures of spatial perception in Linn and Petersen's (1985) threefold model as well as of extrinsic-static skills in Newcombe and Shipley's (2014) two-dimensional classification and can be used to assess the *Frame of Reference Illusions* factor in Buckley et al.'s (2018) extension of the CHC theory.

The Relevance of Sex Differences in Spatial Ability

From an educational perspective, studying cognitive sex differences can provide valuable insight into sources of inequality and performance disparities, inform the development of individualized and targeted support approaches aimed at improving overall performance, and contribute to a broader understanding of how individuals learn (Halpern, 2013). Within this context, spatial skills warrant particular attention, as they play a key role in the development of proficiency in Science, Technology, Engineering, and Mathematics (STEM) domains (Kell & Lunisky, 2013; Khine, 2017). Accordingly, sex differences in spatial abilities have been proposed as one potential driver of the persistent underrepresentation of women in STEM education and occupations (Baker & Cornelson, 2018; Signorella & Liben, 2024).

Spatial ability has repeatedly been related to educational performance in mathematics and science. For example, spatial task performance of children at preschool (Frick, 2019; Wolfgang et al., 2001) and primary school age (Gilligan et al., 2017; Gunderson et al., 2012) has been found to predict their later mathematics achievement. Recent meta-analytical evidence further yielded a moderate association between spatial and mathematical skills (Atit et al., 2022; Xie et al., 2025), with converging evidence from studies specifically applying WLTs (Scott et al., 2023; Voyer, 1998). Moreover, performance in spatial measures has been identified as a unique predictor of later STEM attainment and achievement (Uttal et al., 2013b). Several large-scale longitudinal investigations have shown that adolescents with higher spatial scores later preferred math and science courses in high school, tended to choose degrees and careers in STEM fields (Shea et al., 2001; Wai et al., 2009; Webb et al., 2007), and produced more creative scientific output (Kell et al., 2013).

Importantly, spatial skills are not only predictive of later achievement but are also malleable. In a meta-analysis, Uttal et al. (2013a) found moderate training effects for extrinsic-static skills (i.e., spatial perception) measured with WLTs and other spatial skills, indicating that spatial cognition can be effectively improved through spatially related experiences and dedicated training. Further evidence suggests that spatial training can improve STEM achievement (Cheng & Mix, 2014; Hawes et al., 2022; Miller & Halpern, 2013), with some studies pointing to particularly strong gains in girls and women. For example, reduced retention rates of female engineering students (Sorby et al., 2018) and pronounced improvements in mathematics performance among adolescent girls (Sorby & Veurink, 2019) have been observed following spatial training.

WLTs have been specifically associated with educational outcomes in geosciences (Liben & Titus, 2012). Performance on WLTs has been linked to several indicators of expert level understanding in geology, including comprehension of plate tectonics (Polifka et al., 2023), hydrogeology knowledge and performance (McNeal et al., 2024), and the interpretation of strike and dip, i.e., the orientation of planar geologic features (Bower & Liben, 2023; Liben et al., 2011; Johanesen et al., 2024). Consistent with these associations, geology experts have demonstrated superior WLT performance relative to non-experts in WLTs (McNeal et al., 2024). Similar WLT-based differentiations between experts and non-experts have further been reported in other spatially intensive domains including several STEM disciplines (Kalichman, 1986; Nordvik & Amponsah, 1998; Tomai et al., 2024), visual arts (Goldsmith et al., 2016), and professional orienteering (Feraco, 2025; Taufer, 2021).

Sex differences in WLT performance may therefore represent one factor contributing to sex-related disparities in participation, achievement, and expertise across STEM and other spatially related fields. A better understanding of these sex differences, along with potential moderating factors, may thus help inform interventions aimed at reducing performance disparities and broadening participation in STEM domains. Given the substantial variability in test designs and sample compositions across the WLT literature, meta-analytical investigation is needed to integrate the heterogenous literature and to clarify the magnitude and robustness of sex differences in WLT performance.

Meta-Analyses on Sex Differences in WLT Performance: Past and Present Research

Previous meta-analyses have repeatedly shown sex differences favoring male participants in tests of spatial perception (i.e., extrinsic-static ability) generally (Linn & Petersen, 1985; Voyer et al., 1995) and in WLTs specifically (Pietschnig & Voracek, 2011; Voyer et al., 1995). Therefore, positive effect size estimates in the following section consistently reflect male advantages.

Linn and Petersen (1985) conducted the first meta-analysis including WLTs as part of their examination of sex differences in spatial cognition (i.e., spatial perception, mental rotation, and spatial visualization). For spatial perception, they analyzed 62 effect sizes from 23 studies employing WLTs or the RFT, yielding moderate sex differences in favor of men (d = 0.44). However, they did not report a summary effect specific to WLTs. This was first done by Voyer et al. (1995) in their meta-analytical investigation of sex differences in 12 different spatial tasks. They included 62 effect sizes from 25 studies in their analysis, yielding moderate sex differences favoring male participants (d = 0.42). The most recent meta-analysis was conducted by Pietschnig and Voracek (2011), who also reported moderately sized, yet slightly larger, sex differences with male advantages (d = 0.55) based on their meta-analysis of 157 independent samples from 89 studies.

In addition to the consistent finding of moderate sex differences favoring men in WLT performance, most meta-analyses have shown increasing effect sizes with age (Linn & Petersen, 1985; Pietschnig & Voracek, 2011; Voyer et al., 1995). Moreover, in the most recent investigation, stability of the magnitude of the effect across publication years was reported (Pietschnig & Voracek, 2011). To obtain a comprehensive understanding of these patterns, and to account for recent evidence that suggests declining effect strengths over time in psychological research (Pietschnig et al., 2019; Protzko & Schooler, 2017) it is necessary to synthesize the more than 60 years of research on this topic. Moreover, the robustness of the observed sex difference across different conditions remains unclear. Specifically, little is known about its generalizability with respect to the version of the WLT administered, the characteristics of the sample tested, or the meta-analytical model used.

The present research involves a meta-analysis of sex differences in Piaget's Water Level Tasks. In addition to the summary effect, evidence on cross-temporal trajectories as well as the potential impact of moderating variables and dissemination biases is presented. Finally, robustness across different test-, sample-, and meta-analytical model-related specifications is demonstrated by means of multiverse analyses.

Methods

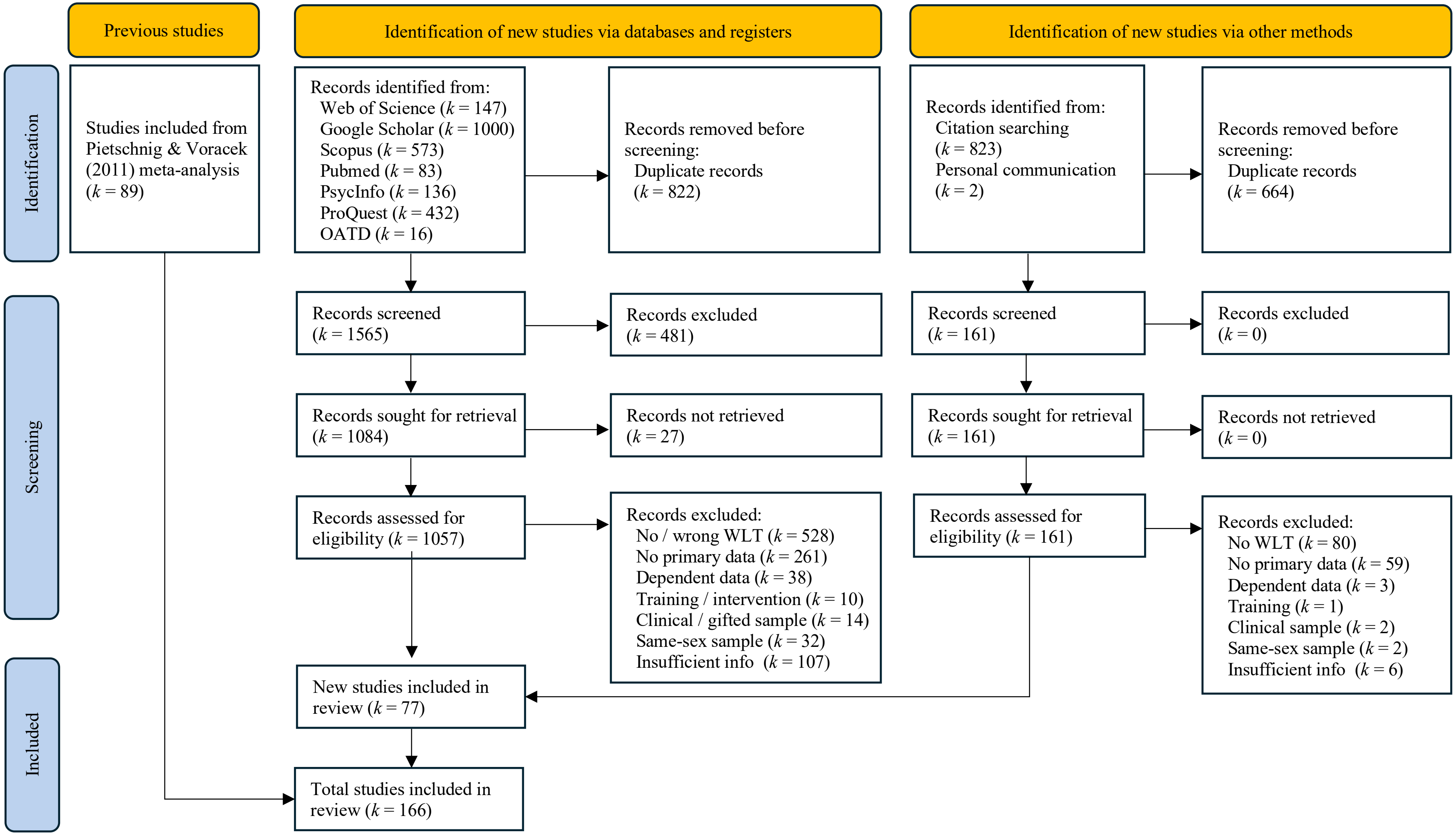
This study was preregistered at the Open Science Framework (OSF; https://osf.io/zdwfh) before accessing any data. All deviations from the preregistered protocol are documented in Appendix B (see Table S1). The Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) checklist (Page et al., 2021) is provided in Appendix C (see Table S2).

Literature Search

As a basis for this research, the studies included in the most recent meta-analysis by Pietschnig and Voracek (2011), as provided by its authors, were used. Where available, relevant information (see Coding section below for details) was re-extracted and recoded, and effect sizes were re-calculated. To update these data, an extensive literature search using five databases for published studies (ISI Web of Science, Google Scholar, Scopus, PsycInfo, PubMed) as well as ProQuest and the Open Access Theses and Dissertations (OATD) database for grey literature was conducted by one researcher [FD]. To obtain potentially relevant studies, the following search string was used: "water level task" OR "water level test" OR "water level experiment" OR "water level representation" OR "water line task" OR "water level concept" OR "liquid horizontality“ OR "Piaget water" OR "Piaget horizontal*" OR "Piaget spatial*" OR "Wasserspiegelaufgabe". Second, a cited reference search for previous meta-analyses (i.e., Linn & Petersen, 1985; Pietschnig & Voracek, 2011; Signorella & Jamison, 1986; Voyer et al., 1995) was performed. Third, reference lists of studies identified as eligible for inclusion were screened for further hits. Titles and abstracts of the resulting hits were screened for eligibility and full texts of potentially includable studies were obtained. Studies with abstracts or full texts not written in English, German, or French were translated with the online translator DeepL (https://www.deepl.com/en/translator). From a total of 2,387 hits, 1,565 titles and abstracts were screened after deduplication, and full texts of 1,057 studies were inspected for eligibility (see Fig. 8 for a flowchart). Excluded studies along with the reasons for their exclusion are provided in Appendix D. The original literature search was performed from April to June 2024 and updated in May 2025.

Figure 8

PRISMA Flowchart.



Inclusion Criteria

To be eligible for inclusion in the present meta-analysis, studies had to meet nine criteria: (i) A WLT had to be used and (ii) sex differences had to be reported, or the information provided had to allow the calculation of an effect size. (iii) samples had to be healthy as well as (iv) independent from each other, and (v) should not average more than two standard deviations above or below the mean in terms of their cognitive abilities. Regarding the version of the WLT used, (vi) the test had to provide either a 2D drawing on paper or on a PC, a photograph or real vessels as stimuli. Test responses (i.e., the indication of the water level) had to (vii) be drawn by hand (pen-and-paper version), selected from a series of alternatives (MC version), adapted using a model of the water level (e.g., with a ruler, a thread, etc.) or adapted using a model of the vessel. (viii) If a reference was provided in the test, it had to be horizontal. Finally, (ix) no trainings or interventions could be implemented before the test. The first author [FD] screened titles, abstracts, and full texts for eligibility and coded relevant information following the scheme below. Ambiguities were discussed and resolved with an independent researcher [JP].

Coding

Relevant information from eligible studies were coded twice independently by the same researcher [FD]. Inconsistencies in coding were resolved by discussing them with an independent coder [JP]. Coding included the following information:

- Reference : The full reference of the study following guidelines provided by the American Psychological Association (APA; APA, 2020).
- Source: Where the study was found, categorized as (i) Pietschnig (i.e., the study was included in the dataset from the meta-analysis by Pietschnig and Voracek, 2011), (ii) Scholar (i.e., Google Scholar), (iii) WoS (i.e., ISI Web of Science), (iv) Scopus, (v) OATD, (vi) ProQuest, (vii) CitedRef (i.e., forward citation search of previous meta-analyses), (viii) Author (i.e., unpublished data provided by the author).
- Publication characteristics: The sex of the first author, categorized as (i) male and (ii) female, the year of publication, the year the data were collected, the country in which the first author was affiliated, and the status of publication, categorized as (i) published and (ii) unpublished.
- Sample characteristics: The total sample size, the percentage of male participants, the mean participant age, their age group, categorized as (i) children (i.e., up to age 10), (ii) adolescents (i.e., age 11 to 17), adults (i.e., from age 18), mean birth year of

participants, and the type of sample, categorized as (i) university students (i.e., participants were recruited in their university or college), (ii) pupils (i.e., participants were recruited in their school), (iii) healthy control group (i.e., participants were the control group in a clinical study), (iv) general population (i.e., participants were recruited as a representative sample of the population of the location where the study was conducted), (v) other (i.e., participants were part of another specific group), the origin of the sample (i.e., the country of data collection), (vi) the mean education level of the sample.

- Test characteristics: The number of items administered, the number of practice items provided, the shape of the vessel used, categorized as (i) rectangular, (ii) Florence flask, (iii) cylindrical, (iv) pitcher, (v) bottle, (vi) bucket, (vii) glass/cup, (viii) jar, (ix) mixed shapes, the mode of stimulus presentation, categorized as (i) drawing (i.e., pen-and-paper format), (ii) real vessel (i.e., the stimulus consisted of a physical model), (iii) photograph, (iv) screen, (v) mixed, the presence of a horizontal cue (i.e., whether a horizontal reference line was provided underneath the stimuli), the response format, categorized as (i) draw water level (WL), (ii) MC, (iii) adjust WL (i.e., participants responded by adjusting the water line in a model with a fixed vessel), (iv) adjust vessel (i.e., participants responded by adjusting the vessel in a model with a fixed water line), the test setting (i.e., whether the test was administered in an (i) individual- or in a (ii) group setting), the sex of the experimenter, the mode of instruction, characterized as (i) verbal, (ii) written, (iii) verbal and written, (iv) written and read aloud, and the test mode (i.e., whether a (i) power- or a (ii) speeded version of the WLT was used).
- Outcome characteristics: The outcome measure, characterized as (i) mean deviation from the horizontal in degrees, (ii) mean number of correct items, (iii) percentage of correct items, (iv) mean number of erroneous items, (v) number of successful subjects (i.e., the number of subjects that successfully solved the WLT), (vi) other, the effect metric (i.e., the metric of the sex difference, if reported), *p*-value (i.e., the *p*-value for the reported sex differences), and effect sizes (i.e., Cohen's *d* and Hedge's *g*) along with their variances.

In case of missing information, requests were sent to corresponding primary study authors via email. If no response was received, reminders were sent after two and four weeks. If the information required to calculate an effect sizes was not provided or the corresponding authors did not respond, studies were excluded from further analyses.

Data Analysis

If not reported, standardized mean sex differences in Cohen's *d* and Hedge's *g* were calculated, with positive values indicating male advantages. The resulting effect sizes were weighted according to study precision (i.e., higher weights were assigned to more precise studies according to the inverse variances of effect sizes) and synthesized in maximum-likelihood estimated random-effects meta-analyses (Hedges & Olkin, 1985). Study heterogeneity was assessed using I^2, a measure that provides the percentage of total variability attributable to true between-study variation rather than sampling error (Borenstein et al., 2021). In line with established guidelines (Higgins et al., 2003), I^2 values of 25%, 50%, and 75% were interpreted as the lower thresholds of small, moderate, and large heterogeneity, respectively. Robustness of the summary effect was examined by means of influence diagnostics (i.e., standardized residuals, difference in fits (DFFITS) values, Cook's distances, covariate ratios, hat values, and weights; Viechtbauer & Cheung, 2010) and a leave-one-out sensitivity analysis. Effect sizes of Cohen's *d*s were interpreted according to the classification of Funder and Ozer (2019) with absolute d = 0.10, 0.20, 0.41, 0.63, and 0.87 as bottom thresholds of very small, small, medium, large, and very large effects, respectively.

Subgroup Analyses

To examine potential influences of categorical moderators, a series of subgroup analyses were conducted. Effect sizes were grouped according to response format (MC vs. draw WL vs. adjust WL), test setting (group vs. individual setting), the presence of a horizontal reference line (provided vs. not provided), test mode (power vs. speed test), sex of the first author (male vs. female), shape of vessel (rectangular vs. bottle vs. Florence flask vs. jar vs. cylindrical vs. mixed shapes), mode of stimulus presentation (drawing vs. screen vs. real vessel), sample continent of origin (North America vs. Europe vs. Asia vs. Africa vs. Australia) and sample type (undergraduate students vs. pupils vs. healthy control group vs. general population vs. other). In these analyses, a mixed-effects approach was used, i.e., within-subgroup estimates were compared using random-effects models, and between-subgroup comparisons were based on fixed-effects models.

Meta-regression

Continuous moderators were investigated using precision-weighted linear meta-regressions. As declining effect strengths over time have been observed in research on cognitive abilities (Pietschnig et al., 2019), potential impacts of publication year on the effect sizes were examined. An exploratory cumulative meta-analysis according to publication year was additionally conducted to further investigate cross-temporal trajectories. Moreover, the effect sizes were regressed on mean participant age to investigate whether increasing sex differences with age found in previous meta-analyses (Linn & Petersen, 1985; Pietschnig & Voracek, 2011; Voyer et al., 1995) hold true considering all studies conducted to date. To examine potential cohort effects, a meta-regression with birth year was computed. Finally, as the length of the WLTs varied considerably between studies, a meta-regression for effect sizes on the number of administered items was calculated.

Dissemination Bias

Considering the strengths and weaknesses of individual detection methods of dissemination bias and thus the lack of a gold standard, triangulation of different standard and more modern methods has recently been advocated (Siegel et al., 2022). Therefore, ten methods to examine confounding dissemination bias (see Appendix E for descriptions of the different bias detection techniques) were employed.

Multiverse and Specification Curve Analyses

While the influence of several moderating variables has previously been tested (Pietschnig & Voracek, 2011, Voyer et al., 1995), their interactions with different analytical approaches have thus far not been tested systematically. Therefore, the generality of the observed summary effect across variations in test design, sample composition, and meta-analytical modeling is yet to be examined. To fill this gap, specification curve and multiverse meta-analyses were conducted to assess the influence of different (reasonable) ways of which data to include and how to meta-analytically synthesize them (Voracek et al., 2019).

These approaches have previously been applied to evaluate the generalizability of empirical findings across diverse psychological research questions. For example, specification curve and multiverse meta-analyses have been used to demonstrate the robustness of the association between psychometric intelligence and self-assessed intelligence (Patzl et al., 2024) as well as religiosity (Dürlinger & Pietschnig, 2022), to support the effectiveness of digital interventions in treating depression (Plessen et al., 2025), or to uncover the lack of evidence supporting a Mozart effect in the context of epilepsy (Oberleiter & Pietschnig, 2023). Multiverse meta-analytical approaches thus provide a powerful methodological framework for obtaining a more nuanced understanding of the influence of researcher degrees of freedom that lead to variability in procedural and analytical decisions and therefore to heterogeneous or even conflicting results.

The two conceptually similar approaches were introduced for the analysis of primary data by Simonsohn et al. (2015) and Steegen et al. (2016), respectively, and adapted by Voracek et al. (2019) for meta-analysis. They both involve the identification of theoretically reasonable specifications which data to analyze and how to analyze them (so-called *which* and *how* factors) followed by the combinatorial synthesis of these specifications (i.e., statistically analyzing all of them) and a graphical display of the results. Specification curve meta-analysis includes inferential testing of the resulting descriptive specification curve via parametric bootstrapping along with a visualization of this procedure with an inferential specification curve. Multiverse meta-analysis deviates from this procedure as results are visualized with a histogram of the *p*-value distribution for the meta-analytical summary effects of all specifications and are not tested inferentially (Voracek et al., 2019).

Here, nine *which* factors were used, including sex of the first author (male vs. female vs. either), age group (children vs. adolescents vs. adults vs. either), sample type (undergraduates vs. other vs. either), participant origin (North America vs. other vs. either), response mode (draw WL vs. other vs. either), publication status (yes vs. no vs. either), test setting (individual vs. group vs. either), presence of a horizontal reference line (yes vs. no vs. either), and vessel shape (rectangular vs. other vs. either). Moreover, two *how* factors were used, including effect size metric (Cohen's *d* vs. Hedge's *g*) and type of meta-analysis (fixed-effects vs. random-effects restricted maximum-likelihood). The combination of 26,244 *which* factors (3 * 4 * 3 * 3 * 3 * 3 * 3 * 3 * 3) and 4 *how* factors (2 * 2) resulted in 104,976 reasonable specifications, of which 12,792 yielded at least two independent effect sizes, allowing the calculation of a summary effect.

To inferentially test the descriptive specification curve against the null hypothesis of no effect, a parametric bootstrapping method was used. Assuming a true effect of zero and all study characteristics as fixed, new effect sizes were randomly generated with standard deviations corresponding to the standard errors observed in the primary studies. This procedure was repeated 1,000 times, yielding 1,000 bootstrapped specification curves from which pointwise 2.5% and 97.5% quantiles were calculated to obtain the lower and upper boundaries of the null hypothesis for each specification number. Where the observed descriptive specification curve exceeded these boundaries, a non-null summary effect was assumed.

Combinatorial Meta-Analysis

Because the selection of relevant *which* and *how* factors should be informed by prior evidence, the identification of reasonable specifications for specification curve and multiverse meta-analyses inevitably involves subjective judgement. Therefore, relevant specifications may be overlooked when certain moderators have not been conceptually identified in previous literature (Oberleiter & Pietschnig, 2023; Voracek et al., 2019). To address these remaining researcher degrees of freedom, it has been suggested to complement multiverse meta-analytic approaches with combinatorial meta-analysis (Olkin et al., 2012).

This brute-force approach involves the estimation of summary effects for all possible subsets of studies in a fixed-effect meta-analysis rather than focusing on reasonable specifications. It allows for the exploratory detection of potential moderators and influential studies based on distribution characteristics in summary effect size and between-study heterogeneity. However, meta-analyzing all $2^k - 1$ possible combinations, which would presently require roughly 5.8 quinvigintillion unique subsets (2^{261} = 57,896,044,618,658,097, 711,785,492,504,343,953,926,634,992,332,820,282,019,728,792,003,956,564,819,968), likely involves many unreasonable specifications and often exceeds the computational capacity of standard computers. Therefore, a random sample of 100,000 subsets was drawn out of these possible combinations for the present combinatorial meta-analysis. To address the influence of outliers, a stratified approach was used, oversampling studies with the smallest and largest effects. The resulting GOSH (graphical display of study heterogeneity) plot was visually examined to investigate the distribution of summary effects and associated between-studies heterogeneity when using any specification, and dispersion values were numerically inspected. This provided insights into interpretability (i.e., symmetrical distributions and narrow intervals implied well-interpretable summary effects) and allowed the identification of potentially influential studies.

Analysis Software

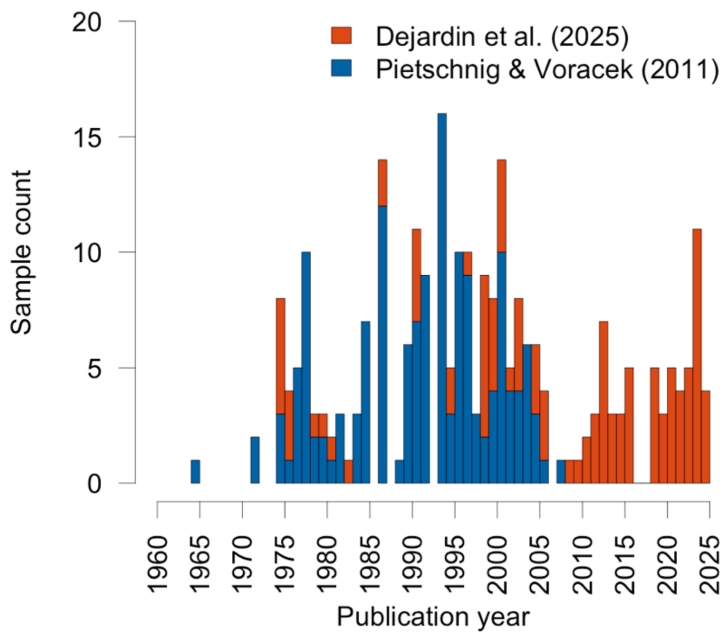
Data analyses were performed using the open-source software R version 4.3.3 (R Core Team, 2024). The analysis code used for the present analyses is available in Appendix F. For the illustration of sample origins, R code adapted from Oberleiter et al. (2023) was used. The original code is available at https://osf.io/3qjrd/files/kax59 (accessed on 28 December 2025). For specification curve, multiverse, and combinatorial meta-analysis, R code from Voracek et al. (2019) was used and is available at https://osf.io/nkv46 (accessed on 06 June 2025). Dissemination bias detection analyses were performed by means of the online application MetaShine (Siegel et al., 2021).

Results

Final Sample

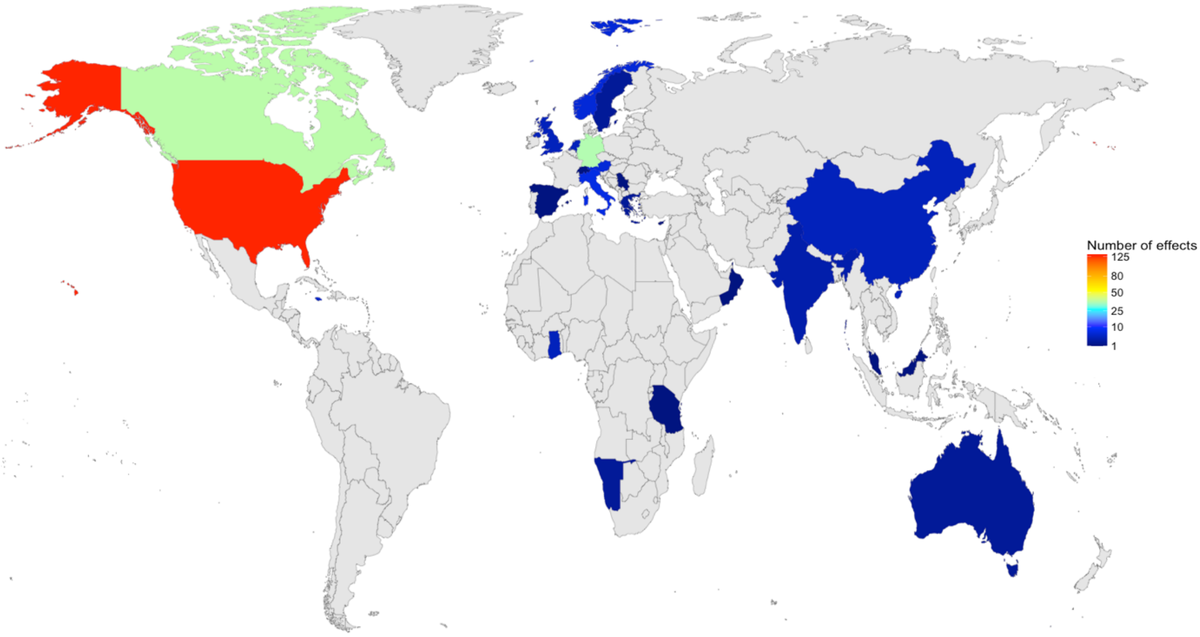
In all, effect sizes of 89 studies from Pietschnig and Voracek (2011) and 77 newly identified studies were included in the present meta-analysis (see Fig. 9). The final sample was composed of effect sizes from 267 independent samples of 166 studies from 1964 to 2025, of which 140 were published and 26 were unpublished. Participants (*N* = 38,402; *n*-range: 5 to 1520) were born between 1901 and 2017 and were aged 18.63 years on average (*SD* = 11.05, median = 18.00, age range: 5.00 to 79.00, inter quartile range: 11.30 to 21.35). Most samples originated from WEIRD (Western, Educated, Industrialized, Rich, Democratic) countries, with almost half coming from North America (see Fig. 10 for an illustration of sample origins). The majority of samples further comprised undergraduate students at colleges or universities (*k* = 110) and elementary or secondary school pupils (*k* = 96). Of note, 93% of included effect sizes were positive (i.e., indicated male advantages) with Cohen's *d*s ranging from -0.56 to 1.84. Characteristics of included studies are detailed in Table 1.

Figure 9. *Number of Included Effect Sizes per Publication Year.*



Note. Effect sizes included by Pietschnig & Voracek (2011) are depicted in blue. Effect sizes from studies identified in the literature search for the present meta-analysis are depicted in red.

Figure 10. *Heat Map of Sample Countries of Origin.*



Note. Color intensity reflects the number of effect sizes contributed by studies conducted in each country, with warmer colors indicating larger and cooler colors indicating smaller numbers; grey shading represents countries for which no studies were included.

Main Analysis

A precision-weighted random-effects meta-analysis of sex differences in WLT performance resulted in a summary effect of $d = 0.50$ (95% CI [0.47, 0.54], $p < .0001$) and $g = 0.50$ (95% CI [0.46, 0.53], $p < .0001$), respectively (see Fig. 11 for a forest plot), indicating male advantages with moderate effect size. Between-studies heterogeneity was moderate ($Q(266) = 595.84$, $p < .0001$, $I^2 = 53.12\%$), suggesting the presence of influential moderating variables. Outlier analyses using influence diagnostics (see Fig. S1 in Appendix G) and a leave-one-out sensitivity analysis of heterogeneity test statistics yielded three potential leverage points. As re-calculations without these data points did not lead to substantial summary effect changes, the remaining analyses were conducted without omitting these data.

Table 1. *Characteristics of Included Studies.*

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Rebelsky (1964)	128	46.09	undergrad	23.00	USA	p	Pietschnig	paper	4	rect	draw WL	0.322
Morris (1971)	64	50.00	undergrad	20.50	USA	p	Pietschnig	paper	4	rect	draw WL	0.507
Morris (1971)	64	50.00	undergrad	20.50	USA	p	Pietschnig	paper	4	rect	draw WL	0.219
De Avila & Havassy (1974)	1180	49.75	pupils	9.72	Canada	p	Pietschnig	paper	17	rect	draw WL	0.026
Liben (1974)	50	54.00	pupils	9.00	USA	p	Pietschnig	paper	4	rect	draw WL	0.501
Liben (1974)	44	45.45	pupils	9.00	USA	p	Pietschnig	paper	4	rect	draw WL	0.987
Mitchelmore (1974)	16	50.00	pupils	9.60	Jamaica	np	ProQuest	paper	4	bottle	draw WL	0.944
Mitchelmore (1974)	16	50.00	pupils	11.15	Jamaica	np	ProQuest	paper	4	bottle	draw WL	1.305
Mitchelmore (1974)	16	50.00	pupils	12.75	Jamaica	np	ProQuest	paper	4	bottle	draw WL	0.319
Mitchelmore (1974)	16	50.00	pupils	14.40	Jamaica	np	ProQuest	paper	4	bottle	draw WL	-0.227
Mitchelmore (1974)	127	42.52	pupils	14.50	Jamaica	np	ProQuest	paper	4	bottle	draw WL	0.185
Thomas & Jamison (1975)	134	46.27	undergrad	19.42	USA	p	Pietschnig	real vessel	48	rect	adjust WL	0.540
Maxwell et al. (1975)	35	51.43	pupils	8.96	USA	p	Scholar	paper	8	cylindrical	draw WL	0.816
Miller (1975)	16	50.00	pupils	9.90	Canada	np	ProQuest	paper	16	NA	draw WL	0.422
Miller (1975)	24	50.00	pupils	9.90	Canada	np	ProQuest	paper	16	NA	draw WL	-0.367

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Geiringer (1976)	60	50.00	pupils	36.94	USA	np	Pietschnig	real vessel	24	florence flask	adjust WL	0.624
Geiringer (1976)	40	50.00	pupils	64.28	USA	np	Pietschnig	real vessel	24	florence flask	adjust WL	0.465
Geiringer (1976)	40	50.00	pupils	75.40	USA	np	Pietschnig	real vessel	24	florence flask	adjust WL	0.554
Geiringer & Hyde (1976)	60	50.00	pupils	11.00	USA	p	Pietschnig	real vessel	24	florence flask	adjust WL	0.512
Geiringer & Hyde (1976)	60	50.00	pupils	18.00	USA	p	Pietschnig	real vessel	24	florence flask	adjust WL	0.424
Abravanel & Gingold (1977)	50	52.00	pupils	9.58	USA	p	Pietschnig	paper	5	cylindrical	draw WL	0.307
Abravanel & Gingold (1977)	50	48.00	pupils	9.90	USA	p	Pietschnig	paper	5	bottle	draw WL	0.416
Abravanel & Gingold (1977)	30	46.47	pupils	10.16	USA	p	Pietschnig	paper	5	cylindrical	draw WL	-0.010
Harris et al. (1977)	158	30.38	NA	NA	NA	p	Pietschnig	paper	16	mixed shapes	MC	0.953
Harris et al. (1977)	61	54.10	NA	NA	NA	p	Pietschnig	paper	16	mixed shapes	MC	0.812
Harris et al. (1977)	158	33.54	NA	NA	NA	p	Pietschnig	paper	16	mixed shapes	MC	0.854

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Harris et al. (1977)	110	40.91	NA	NA	NA	p	Pietschnig	paper	16	mixed shapes	MC	0.334
Harris et al. (1977)	69	20.29	NA	NA	NA	p	Pietschnig	paper	16	mixed shapes	MC	0.036
Harris et al. (1977)	110	52.73	NA	NA	NA	p	Pietschnig	paper	16	mixed shapes	MC	1.544
Kelly J. & Kelly G. (1977)	314	39.17	undergrad	NA	USA	p	Pietschnig	paper	12	rect	draw WL	0.548
McGillicuddy-DeLisi et al. (1978)	20	50.00	undergrad	NA	USA	p	Pietschnig	paper	3	jar	draw WL	0.979
Walker & Krasnoff (1978)	88	50.00	undergrad	NA	USA	p	Pietschnig	paper	15	mixed shapes	draw WL	0.439
Liben (1978)	66	50.00	pupils	17.50	USA	p	Scholar	paper	10	mixed shapes	draw WL	0.617
McGiffert-Spradlin et al. (1979)	120	50.00	undergrad	NA	USA	p	Pietschnig	paper	5	rect	draw WL	1.016
Ray et al. (1979)	135	37.04	undergrad	NA	USA	p	Pietschnig	paper	4	rect	draw WL	0.306
Morgan (1979)	102	50.98	pupils	15.48	USA	np	ProQuest	paper	6	florence flask	draw WL	0.806
Treagust (1980)	108	50.00	pupils	15.80	USA	p	Pietschnig	paper	NA	rect	draw WL	0.859
Liben & Golbeck (1980)	240	50.00	pupils	12.62	USA	p	Scholar	paper	6	rect	draw WL	0.469

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Thompson et al. (1981)	136	19.19	undergrad	20.00	USA	p	Pietschnig	paper	5	pitcher	draw WL	0.522
Walker et al. (1981)	129	48.84	other	44.12	USA	p	Pietschnig	paper	12	rect	draw WL	0.152
Walker et al. (1981)	129	48.06	pupils	16.66	USA	p	Pietschnig	paper	12	rect	draw WL	0.668
Pearson (1982)	350	43.71	undergrad	NA	USA	np	Scholar	paper	12	mixed shapes	MC	0.775
Krasnoff & Walker (1983)	213	53.99	undergrad	NA	USA	p	Pietschnig	paper	12	rect	draw WL	0.411
Linn & Pulos (1983)	778	51.80	pupils	14.89	USA	p	Pietschnig	paper	8	rect	draw WL	0.376
Tegano & Faulkender (1983)	113	37.17	undergrad	NA	USA	p	Pietschnig	paper	2	NA	draw WL	0.808
Kenyon (1984)	30	50.00	undergrad	NA	Canada	p	Pietschnig	paper	8	cylindrical	draw WL	1.383
Liben & Golbeck (1984)	40	50.00	undergrad	19.25	USA	p	Pietschnig	paper	6	rect	draw WL	0.878
Liben & Golbeck (1984)	40	50.00	undergrad	19.25	USA	p	Pietschnig	paper	6	rect	draw WL	0.615
Liben & Golbeck (1984)	80	50.00	undergrad	19.55	USA	p	Pietschnig	paper	6	rect	draw WL	0.854
Mowrer-Popiel & DeLisi (1984)	125	31.20	undergrad	23.00	USA	p	Pietschnig	paper	11	NA	draw WL	0.493

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Myer & Higgins-Hensley (1984)	85	48.24	undergrad	19.00	USA	p	Pietschnig	paper	2	rect	draw WL	0.554
Wittig & Allen (1984)	195	37.95	undergrad	18.80	USA	p	Pietschnig	mixed	72	mixed shapes	mixed	0.573
Golbeck (1986)	64	50.00	undergrad	21.00	USA	p	Pietschnig	paper	6	rect	draw WL	0.721
Kalichman (1986)	50	50.00	undergrad	NA	USA	p	Pietschnig	paper	8	mixed shapes	draw WL	1.231
Kalichman (1986)	50	50.00	undergrad	NA	USA	p	Pietschnig	paper	8	mixed shapes	draw WL	1.047
Kalichman (1986)	50	50.00	undergrad	NA	USA	p	Pietschnig	paper	8	mixed shapes	draw WL	1.271
Kalichman (1986)	50	50.00	undergrad	NA	USA	p	Pietschnig	paper	8	mixed shapes	draw WL	1.123
Kalichman (1986)	50	50.00	undergrad	NA	USA	p	Pietschnig	paper	8	mixed shapes	draw WL	1.254
Liben & Golbeck (1986)	40	50.00	undergrad	20.00	USA	p	Pietschnig	paper	6	rect	draw WL	0.697
Meehan & Overton (1986)	84	50.00	undergrad	18.92	USA	p	Pietschnig	paper	6	rect	draw WL	0.531
Meehan & Overton (1986)	30	40.00	undergrad	21.25	USA	p	Pietschnig	paper	6	rect	draw WL	0.567

Table 1 (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Murphy-Berman, et al. (1986)	15	46.67	pupils	10.28	USA	p	Pietschnig	paper	24	rect	draw WL	0.730
Murphy-Berman, et al. (1986)	15	46.67	pupils	10.28	USA	p	Pietschnig	paper	24	rect	draw WL	1.191
Sanders & Ross-Field (1986)	16	50.00	undergrad	25.00	England	p	Pietschnig	paper	10	rect	draw WL	1.701
Batey (1986)	23	65.22	pupils	15.50	USA	np	ProQuest	paper	20	mixed shapes	draw WL	-0.357
Batey (1986)	153	52.94	pupils	13.00	USA	np	ProQuest	paper	20	mixed shapes	draw WL	1.048
Otani & Leonard (1988)	153	24.18	undergrad	NA	USA	p	Pietschnig	paper	6	mixed shapes	draw WL	0.440
Kalichman (1989a)	194	50.00	undergrad	NA	USA	p	Pietschnig	paper	3	rect	draw WL	0.788
Kalichman (1989b)	104	50.00	undergrad	NA	USA	p	Pietschnig	paper	3	mixed shapes	draw WL	0.522
Krasnoff et al. (1989)	80	50.00	undergrad	NA	USA	p	Pietschnig	paper	12	rect	draw WL	0.846
Robert & Chaperon (1989)	1520	32.11	undergrad	20.00	Canada	p	Pietschnig	paper	1	cylindrical	draw WL	0.542
Sholl (1989)	477	33.75	undergrad	NA	USA	p	Pietschnig	paper	16	mixed shapes	draw WL	0.446

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Signorella et al. (1989)	344	57.56	undergrad	NA	USA	p	Pietschnig	paper	4	rect	draw WL	0.533
Beatty & Duncan (1990)	120	49.17	undergrad	22.95	USA	p	Pietschnig	paper	8	rect	draw WL	0.545
Gladue et al. (1990)	31	51.61	general population	27.81	USA	p	Pietschnig	paper	8	rect	draw WL	0.815
Mowrer-Popiel (1990)	140	50.00	other	20.00	USA	np	Pietschnig	paper	6	spherical bottle	draw WL	0.305
Robert (1990)	284	20.77	undergrad	21.95	Canada	p	Pietschnig	paper	8	mixed shapes	draw WL	0.738
Robert, & Tanguay (1990)	32	53.13	other	50.50	Canada	p	Pietschnig	paper	8	mixed shapes	draw WL	0.405
Robert, & Tanguay (1990)	28	46.43	other	67.00	Canada	p	Pietschnig	paper	8	mixed shapes	draw WL	0.364
Robert, & Tanguay (1990)	30	50.00	other	79.00	Canada	p	Pietschnig	paper	8	mixed shapes	draw WL	1.292
Richa (1990)	60	50.00	other	5.00	India	np	Scholar	real vessel	6	jar	adjust vessel	0.708
Richa (1990)	60	50.00	pupils	10.00	India	np	Scholar	real vessel	6	jar	adjust vessel	0.686
Richa (1990)	60	50.00	pupils	16.50	India	np	Scholar	real vessel	6	jar	adjust vessel	0.707

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Lewis & Harris (1990)	56	50.00	undergrad	18.50	USA	p	Scholar	paper	4	mixed shapes	MC	0.428
Kalichman (1991)	76	50.00	undergrad	NA	USA	p	Pietschnig	paper	3	rect	draw WL	1.006
Liben (1991)	104	48.08	undergrad	19.00	USA	p	Pietschnig	paper	6	rect	draw WL	0.506
Liben (1991)	200	50.00	undergrad	19.00	USA	p	Pietschnig	paper	6	rect	draw WL	0.453
McAfee & Proffitt (1991)	442	48.42	undergrad	NA	USA	p	Pietschnig	paper	1	rect	draw WL	0.687
McAfee & Proffitt (1991)	53	35.85	undergrad	NA	USA	p	Pietschnig	paper	24	mixed shapes	draw WL	0.310
McCormick & Witelson (1991)	76	50.00	other	25.00	Canada	p	Pietschnig	paper	6	rect	draw WL	1.056
Pennings (1991)	16	50.00	NA	7.90	Netherlands	p	Pietschnig	paper	10	mixed shapes	draw WL	0.741
Pennings (1991)	16	50.00	NA	7.90	Netherlands	p	Pietschnig	paper	10	mixed shapes	draw WL	0.651
Pennings (1991)	16	50.00	NA	7.90	Netherlands	p	Pietschnig	paper	10	mixed shapes	draw WL	0.941
Robert & Morin (1993)	99	37.37	undergrad	21.60	Canada	p	Pietschnig	paper	4	mixed shapes	draw WL	0.516
Thomas & Lohaus (1993)	38	47.37	pupils	6.50	Germany	p	Pietschnig	paper	8	rect	draw WL	0.487

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Thomas & Lohaus (1993)	55	54.55	pupils	8.00	Germany	p	Pietschnig	paper	8	rect	draw WL	0.470
Thomas & Lohaus (1993)	35	40.00	pupils	9.00	Germany	p	Pietschnig	paper	8	rect	draw WL	0.197
Thomas & Lohaus (1993)	33	63.64	pupils	10.00	Germany	p	Pietschnig	paper	8	rect	draw WL	0.560
Thomas & Lohaus (1993)	63	38.01	pupils	11.00	Germany	p	Pietschnig	paper	8	rect	draw WL	0.480
Thomas & Lohaus (1993)	81	53.09	pupils	12.00	Germany	p	Pietschnig	paper	8	rect	draw WL	0.872
Thomas & Lohaus (1993)	88	52.23	pupils	13.00	Germany	p	Pietschnig	paper	8	rect	draw WL	0.417
Thomas & Lohaus (1993)	58	53.45	pupils	14.00	Germany	p	Pietschnig	paper	8	rect	draw WL	0.253
Thomas & Lohaus (1993)	67	41.79	pupils	15.00	Germany	p	Pietschnig	paper	8	rect	draw WL	0.275
Thomas & Lohaus (1993)	48	54.17	pupils	16.50	Germany	p	Pietschnig	paper	8	rect	draw WL	-0.054
Thomas & Lohaus (1993)	32	50.00	pupils	9.50	Germany	p	Pietschnig	screen	7	rect	adjust WL	0.776
Thomas & Lohaus (1993)	36	55.56	pupils	11.50	Germany	p	Pietschnig	screen	7	rect	adjust WL	0.462

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Thomas & Lohaus (1993)	53	58.49	pupils	13.50	Germany	p	Pietschnig	screen	7	rect	adjust WL	0.489
Thomas & Lohaus (1993)	52	57.69	pupils	16.00	Germany	p	Pietschnig	screen	7	rect	adjust WL	0.531
Vasta, Lightfoot & Cox (1993)	104	46.15	undergrad	19.40	USA	p	Pietschnig	paper	2	rect	MC	0.652
Lawton (1994)	426	32.39	undergrad	24.30	USA	p	Pietschnig	paper	12	mixed shapes	MC	0.807
Robert & Ohlmann (1994)	280	50.00	undergrad	21.20	Canada	p	Pietschnig	paper	8	rect	draw WL	0.721
Robert et al. (1994)	132	45.45	undergrad	23.30	Canada	p	Pietschnig	paper	NA	rect	draw WL	1.217
Agruso (1994)	268	59.70		17.00	USA	np	Scholar	paper	6	rect	draw WL	0.604
Hammer, Hoffer & King (1995)	54	50.00	undergrad	20.00	USA	p	Pietschnig	photo	6	bottle	draw WL	1.837
Hammer, Hoffer & King (1995)	54	50.00	undergrad	25.00	USA	p	Pietschnig	photo	6	bottle	draw WL	0.000
Hecht & Proffitt (1995)	40	40.00	undergrad	25.00	Germany	p	Pietschnig	paper	1	rect	draw WL	0.423
Hecht & Proffitt (1995)	40	40.00	other	38.00	Germany	p	Pietschnig	paper	1	rect	draw WL	0.382
Hecht & Proffitt (1995)	40	40.00	other	51.50	Germany	p	Pietschnig	paper	1	rect	draw WL	1.073

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Parameswaran (1995)	122	28.69	undergrad	22.00	USA	p	Pietschnig	paper	7	rect	draw WL	0.413
Sholl & Liben (1995)	177	29.38	undergrad	NA	USA	p	Pietschnig	paper	8	mixed shapes	draw WL	0.693
Sholl & Liben (1995)	669	30.34	undergrad	NA	USA	p	Pietschnig	paper	6	bottle	draw WL	0.536
Sholl & Liben (1995)	902	42.02	undergrad	NA	USA	p	Pietschnig	paper	6	bottle	draw WL	0.729
Wegesin (1995)	80	50.00	other	28.75	USA	np	Pietschnig	paper	20	rect	draw WL	0.731
Lohaus et al. (1996)	202	47.52	pupils	8.14	Germany	p	Pietschnig	paper	8	rect	draw WL	0.202
Lohaus et al. (1996)	194	53.61	pupils	11.28	Germany	p	Pietschnig	paper	8	rect	draw WL	0.470
Lohaus et al. (1996)	202	54.46	pupils	14.20	Germany	p	Pietschnig	paper	8	rect	draw WL	0.794
Parameswaran & DeLisi (1996)	122	28.69	undergrad	21.90	USA	p	Pietschnig	paper	7	rect	draw WL	0.413
Robert & Harel (1996)	520	55.77	undergrad	22.50	Canada	p	Pietschnig	paper	8	mixed shapes	draw WL	0.671
Robert & Harel (1996)	466	42.92	undergrad	22.50	Canada	p	Pietschnig	paper	8	mixed shapes	draw WL	0.502
Robert & Harel (1996)	426	45.54	undergrad	22.50	Canada	p	Pietschnig	paper	8	mixed shapes	draw WL	0.657
Vasta, Knott & Gaze (1996)	180	46.67	undergrad	21.05	USA	p	Pietschnig	paper	16	rect	draw WL	0.016

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Voyer (1996)	125	56.80	undergrad	19.40	Canada	p	Pietschnig	paper	16	rect	draw WL	0.644
Farace (1996)	155	51.61	other	20.24	USA	np	Scholar	paper	10	jar	draw WL	0.611
Merriwether & Liben (1997)	160	50.00	undergrad	18.90	USA	p	Pietschnig	paper	6	rect	draw WL	0.463
Pulos (1997)	80	50.00	undergrad	NA	USA	p	Pietschnig	paper	4	rect	draw WL	0.324
Pulos (1997)	80	50.00	undergrad	NA	USA	p	Pietschnig	paper	4	rect	draw WL	0.256
Dessens et al. (1998)	142	49.30	healthy control group	32.50	Nether-lands	p	Pietschnig	paper	NA	rect	draw WL	0.627
Wegesin (1998)	40	50.00	other	25.05	USA	p	Pietschnig	paper	20	rect	draw WL	0.727
Voyer (1998)	98	46.94	undergrad	21.20	Canada	p	Scholar	paper	16	mixed shapes	draw WL	0.773
Silver (1998)	52	50.00	other	26.00	USA	p	Scholar	paper	1	bottle	draw WL	0.380
Silver (1998)	66	50.00	pupils	13.50	USA	p	Scholar	paper	1	bottle	draw WL	0.140
Silver (1998)	52	51.92	pupils	10.00	USA	p	Scholar	paper	1	bottle	draw WL	0.074
Nordvic & Amponsah (1998)	161	58.39	undergrad	20.05	Norway	p	Scholar	paper	6	mixed shapes	MC	0.809
Nordvic & Amponsah (1998)	293	23.21	undergrad	22.10	Norway	p	Scholar	paper	6	mixed shapes	MC	0.395

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Epting & Overman (1998)	47	42.55	undergrad	20.08	USA	p	Scholar	paper	8	rect	draw WL	1.093
Li et al. (1999a)	485	52.67	pupils	13.14	China	p	Pietschnig	paper	8	bottle	draw WL	0.281
Li et al. (1999b)	295	36.27	undergrad	20.00	China	p	Pietschnig	paper	8	bottle	draw WL	0.648
Li et al. (1999b)	49	42.86	undergrad	19.00	USA	p	Pietschnig	paper	8	bottle	draw WL	0.483
Li et al. (1999b)	129	46.51	undergrad	19.00	USA	p	Pietschnig	paper	8	bottle	draw WL	0.053
Neave & Menaged (1999)	62	54.84	other	28.67	England	p	Scholar	paper	15	rect	draw WL	0.288
Jovanovic & Lerner (1999)	160	44.00	pupils	11.80	USA	p	Scholar	paper	6	NA	draw WL	0.439
Jovanovic & Lerner (1999)	242	49.00	pupils	12.30	Serbia	p	Scholar	paper	6	NA	draw WL	0.291
Herlitz et al. (1999)	200	50.00	general population	28.10	Sweden	p	Scholar	paper	8	NA	draw WL	0.039
Amponsah (2000)	266	56.02	pupils	12.00	Ghana	p	Pietschnig	paper	6	rect	MC	0.463
Amponsah (2000)	303	49.91	pupils	16.00	Ghana	p	Pietschnig	paper	6	rect	MC	0.383
Amponsah (2000)	390	52.82	undergrad	NA	Ghana	p	Pietschnig	paper	6	rect	MC	0.631
Amponsah (2000)	297	48.15	pupils	12.00	Norway	p	Pietschnig	paper	6	rect	MC	0.690
Amponsah (2000)	310	44.84	pupils	16.00	Norway	p	Pietschnig	paper	6	rect	MC	0.790

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Amponsah (2000)	430	35.81	undergrad	NA	Norway	p	Pietschnig	paper	6	rect	MC	0.594
Amponsah (2000)	249	50.60	pupils	9.00	Ghana	p	Pietschnig	paper	16	rect	MC	0.335
Amponsah (2000)	193	48.70	pupils	9.00	Norway	p	Pietschnig	paper	16	rect	MC	0.327
Amponsah & Krekling (1994)	417	35.73	undergrad	26.00	Ghana and Norway	p	WoS	paper	9	mixed shapes	MC	0.557
Golbeck & Sinagra (2000)	25	0.24	undergrad	22.70	USA	p	Pietschnig	paper	6	rect	draw WL	0.109
Voyer, Nolan & Voyer (2000)	344	42.44	undergrad	19.40	Canada	p	Pietschnig	paper	16	mixed shapes	draw WL	0.571
Lucas & Alwens (2000)	26	46.15	undergrad	NA	USA	np	Scholar	screen	8	NA	draw WL	1.153
Lucas & Alwens (2000)	17	47.06	undergrad	NA	USA	np	Scholar	screen	8	NA	draw WL	-0.354
Lucas & Alwens (2000)	24	50.00	undergrad	NA	USA	np	Scholar	screen	8	NA	draw WL	0.630
Lucas & Alwens (2000)	16	50.00	undergrad	NA	USA	np	Scholar	screen	8	NA	draw WL	0.276
Beisteiner (2001)	1022	54.99	NA	22.97	Austria	np	Pietschnig	paper	12	rect	draw WL	0.277
Casey et al. (2001)	187	48.66	pupils	13.83	USA	p	Pietschnig	paper	8	rect	draw WL	0.670
Quaiser-Pohl (2001)	444	49.77	pupils	9.62	Germany	p	Pietschnig	paper	12	rect	draw WL	0.394
Roberts & Bell (2002)	64	50.00	other	14.04	USA	p	Pietschnig	paper	7	rect	draw WL	0.606

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Lewin et al. (2001)	185	49.19	general population	29.37	Sweden	p	Scopus	paper	10	cylindrical	MC	0.436
Levine & Stern (2002)	89	35.96	undergrad	20.00	USA	p	Pietschnig	paper	6	rect	draw WL	0.616
Seng & Tan (2002)	57	55.36	pupils	10.00	China	np	Pietschnig	paper	8	bottle	draw WL	0.192
Seng & Tan (2002)	38	60.26	pupils	10.00	Malaysia	np	Pietschnig	paper	8	bottle	draw WL	0.347
Seng & Tan (2002)	5	0.40	pupils	10.00	Singapore	np	Pietschnig	paper	8	bottle	draw WL	1.006
Robert & Berthiaume (2002)	46	50.00	other	17.65	Canada	p	Scholar	screen	30	rect	draw WL	0.730
Robert & Berthiaume (2002)	46	50.00	other	17.65	Canada	p	Scholar	screen	240	rect	correct WL yes/no	0.286
Robert & Berthiaume (2002)	46	50.00	other	17.65	Canada	p	Scholar	paper	NA	rect	draw WL	0.057
Robert & Berthiaume (2002)	46	50.00	other	17.65	Canada	p	Scholar	paper	NA	rect	correct WL yes/no	0.460
Formann (2003)	431	52.67	general population	NA	Austria	p	Pietschnig	paper	12	florence flask	draw WL	0.190
Loehlin & McFadden (2003)	255	41.57	other	21.91	USA	p	Pietschnig	paper	NA	rect	draw WL	0.329
Voyer & Sullivan (2003)	140	39.29	undergrad	19.50	Canada	p	Pietschnig	paper	16	rect	draw WL	0.782

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Voyer & Sullivan (2003)	119	42.86	undergrad	19.50	Canada	p	Pietschnig	paper	16	rect	draw WL	0.453
Voyer & Sullivan (2003)	195	46.15	undergrad	19.50	Canada	p	Pietschnig	paper	16	rect	draw WL	0.582
Voyer & Sullivan (2003)	48	43.75	undergrad	19.50	Canada	p	Pietschnig	paper	16	rect	draw WL	1.155
Robert & Héroux (2004)	37	54.05	pupils	9.92	Canada	p	Pietschnig	paper	6	rect	draw WL	0.128
Robert & Héroux (2004)	41	46.34	pupils	12.83	Canada	p	Pietschnig	paper	6	rect	draw WL	0.210
Robert & Héroux (2004)	36	50.00	pupils	15.83	Canada	p	Pietschnig	paper	6	rect	draw WL	0.221
Ecuyer-Dab & Robert (2004)	216	43.98	general population	34.25	Canada	p	Scholar	paper	8	rect	draw WL	0.769
Ansel (2004)	143	48.25	pupils	12.50	USA	np	Scholar	paper	2	rect	draw WL	0.256
Robert & Longpré (2005)	80	50.00	undergrad	23.60	Canada	p	Pietschnig	paper	10	rect	draw WL	0.949
Verdine (2005)	16	50.00	healthy control group	6.20	USA	np	Scholar	paper	4	rect	MC	1.192
Frick (2005)	80	50.00	other	12.06	Switzer-land	np	Scholar	paper	8	rect	draw WL	0.475
Alexander (2005)	120	50.00	undergrad	20.40	USA	p	Scholar	paper	10	jar	draw WL	0.700

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Neumann et al. (2007)	64	50.00	undergrad	19.98	Australia	p	Pietschnig	screen	15	glass/cup	draw WL	0.606
Cherney et al. (2008)	124	48.39	undergrad	19.30	USA	p	Pietschnig	paper	8	rect	draw WL	0.333
Morra (2008)	337	51.04	pupils	8.92	Italy	p	Pietschnig	paper	8	rect	draw WL	0.231
Rilea (2008)	94	50.00	undergrad	NA	USA	p	Pietschnig	screen	216	rect	MC	0.904
Tran & Formann (2008)	147	51.70	general population	NA	Austria	p	Pietschnig	paper	8	florence flask	draw WL	0.243
Tran & Formann (2008)	296	52.70	general population	NA	Austria	p	Pietschnig	paper	8	florence flask	draw WL	0.006
Tran & Formann (2008)	1214	44.65	general population	NA	Austria	p	Pietschnig	paper	8	florence flask	draw WL	0.592
Jansen-Osmann et al. (2008)	20	35.00	pupils	11.80	Germany	p	WoS	paper	NA	rect	draw WL	0.923
Weixelbraun (2009)	143	48.95	general population	34.38	Austria	np	OATD	paper	8	florence flask	draw WL	0.860
Liben et al. (2010)	49	42.86	undergrad	18.50	USA	p	CitedRef	paper	6	rect	Draw WL	0.328
Liben et al. (2011)	125	50.40	undergrad	NA	USA	p	Scholar	paper	6	rect	draw WL	0.195
Christensen (2011)	58	51.72	other	10.03	USA	np	ProQuest	paper	6	rect	draw WL	0.315
Berenbaum et al. (2012)	27	51.85	healthy control group	19.47	USA	p	Scholar	paper	12	bottle	MC	0.873
Cashdan et al. (2012)	103	50.49	other	NA	Tanzania	p	WoS	paper	1	glass/cup	MC	0.606

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Doyle et al. (2012)	403	33.00	undergrad	19.63	USA and Canada	p	WoS	paper	16	mixed shapes	draw WL	0.540
Al-Balushi & Al-Battashi (2013)	101	53.47	pupils	14.50	Oman	p	Scholar	paper	8	bottle	draw WL	0.413
Lange-Küttner & Ebersbach (2013)	18	44.44	pupils	6.58	Germany	p	Scholar	paper	7	NA	draw WL	0.381
Lange-Küttner & Ebersbach (2013)	23	47.83	pupils	7.33	Germany	p	Scholar	paper	7	NA	draw WL	0.045
Lange-Küttner & Ebersbach (2013)	37	54.04	pupils	8.50	Germany	p	Scholar	paper	7	NA	draw WL	-0.256
Lange-Küttner & Ebersbach (2013)	19	52.63	pupils	9.50	Germany	p	Scholar	paper	7	NA	draw WL	-0.521
Ruwisch & Lüthje (2013)	65	61.54	other	6.25	Germany	p	CitedRef	photo	1	bottle	MC	0.212
Gagatsis & Kalogirou (2013)	350	52.29	pupils	12.33	Cyprus	np	CitedRef	paper	1	rect	MC	0.220
Weisberg et al. (2014)	72	50.00	undergrad	22.40	USA	p	WoS	paper	NA	rect	draw WL	0.420
Weisberg & Newcombe (2014)	52	50.00	undergrad	NA	USA	p	Scholar	paper	6	bottle	Draw WL	0.020
Nardi et al. (2014)	40	50.00	undergrad	25.50	Italy	p	CitedRef	paper	6	rect	draw WL	0.184
Holden et al. (2015)	81	39.51	undergrad	21.49	England	p	WoS	paper	13	rect	draw WL	0.457

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Vashro & Cashdan (2015)	122	54.92	other	NA	Namibia	p	Scholar	paper	1	glass/cup	MC	0.429
Coyle (2015)	61	49.18	other	5.17	USA	np	ProQuest	paper	6	jar	MC	-0.384
Merrill et al. (2016)	153	52.29	pupils	9.62	USA	p	WoS	paper	12	jar	draw WL	0.367
Reilly et al. (2016)	309	33.98	undergrad	25.46	Australia	p	Scholar	screen	10	NA	draw WL	0.258
Goldsmith et al. (2016)	53	69.81	pupils	14.50	USA	p	Scopus	paper	6	rect	draw WL	-0.559
Goldsmith et al. (2016)	50	78.00	pupils	14.50	USA	p	Scopus	paper	6	rect	draw WL	0.655
Goldsmith et al. (2016)	28	64.29	pupils	14.50	USA	p	Scopus	paper	6	rect	draw WL	-0.400
Hannula (2019)	82	64.63	undergrad	21.00	Canada	p	Scholar	paper	6	bottle	draw WL	0.290
Sorby et al. (2019)	71	47.89	undergrad	12.50	USA	p	Scopus	paper	6	rect	draw WL	0.320
Sorby et al. (2019)	34	47.06	undergrad	12.50	USA	p	Scopus	paper	6	rect	draw WL	0.421
Sorby et al. (2019)	72	47.22	pupils	12.50	USA	p	Scopus	paper	6	rect	draw WL	-0.493
Smith (2019)	304	35.86	pupils	21.40	Canada	np	CitedRef	screen	6	glass/cup	MC	0.583
Barhorst-Cates et al. (2020)	72	49.30	pupils	9.28	USA	p	WoS	paper	8	rect	draw WL	0.324
Coté & Lalumière (2020)	318	37.11	undergrad	42.60	Canada	p	Scholar	paper	8	rect	draw WL	0.941
Coté & Lalumière (2020)	131	49.62	pupils	40.90	Canada	p	Scholar	paper	8	rect	draw WL	0.567

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Brase (2021)	304	29.27	other	19.96	USA	p	Scholar	screen	7	jar	MC	0.319
Meneghetti et al. (2021)	52	65.38	other	19.10	Italy	p	CitedRef	paper	16	mixed shapes	draw WL	0.461
Meneghetti et al. (2021)	45	60.00	undergrad	20.20	Italy	p	CitedRef	paper	16	mixed shapes	draw WL	0.576
Taufer (2021)	32	56.25	other	24.53	Italy	np	CitedRef	screen	8	bottle	MC	0.379
Davis et al. (2021)	83	34.48	pupils	11.68	Namibia	p	WoS	screen	1	glass/cup	MC	-0.261
Jansen & Pietsch (2022)	92	54.34	other	9.03	Germany	p	Scholar	paper	16	mixed shapes	draw WL	0.455
Kelly & Beltz (2022)	336	33.63	other	19.23	USA	p	Scholar	screen	12	jar	MC	0.432
Rahe & Jansen (2022)	117	38.46	pupils	26.30	Germany	p	WoS	screen	3	bucket	MC	0.467
Kim & Li (2022)	20	50.00	undergrad	21.35	USA	p	CitedRef	paper	10	rect	draw WL	0.454
Polifka et al. (2023)	174	35.63	NA	19.93	USA	p	Scholar	screen	3	rect	draw WL	0.490
Xia & Chen (2023)	30	43.33	undergrad	6.00	China	np	Scholar	screen	4	rect	MC	1.420
Tomai et al. (2024)	28	67.86	undergrad	49.32	Greece	p	Scopus	paper	7	rect	draw WL	0.289
Tomai et al. (2024)	30	30.00	pupils	47.40	Greece	p	Scopus	paper	7	rect	draw WL	0.260
Scott et al. (2023)	154	44.81	other	8.04	England	p	Scholar	paper	16	mixed shapes	draw WL	0.391

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Bracken et al. (2024)	36	38.89	other	5.43	USA	p	WoS	screen	11	jar	draw WL	-0.112
Morawietz et al. (2024b)	25	52.00	pupils	10.70	Germany	p	Scopus	paper	12	jar	draw WL	0.174
Morawietz et al. (2024b)	24	50.00	healthy control group	11.40	Germany	p	Scopus	paper	12	jar	draw WL	1.011
Signorella & Liben (2024)	290	51.03	pupils	19.00	USA	p	Scopus	screen	15	mixed shapes	correct WL yes/no	0.372
McNeal et al. (2024)	71	64.79	pupils	NA	USA	p	Scopus	paper	6	bottle	draw WL	0.237
Hill (2024)	69	47.83	undergrad	20.23	USA	np	CitedRef	paper	4	rect	draw WL	0.987
Morawietz et al. (2024a)	26	50.00	other	11.40	Germany	p	WoS	paper	12	jar	draw WL	-0.310
Morawietz et al. (2024a)	22	40.91	undergrad	12.05	Germany	p	WoS	paper	12	jar	draw WL	0.881
Morawietz et al. (2024a)	26	57.69	pupils	26.10	Germany	p	WoS	paper	12	jar	draw WL	0.159
Morawietz et al. (2024c)	27	44.44	pupils	11.30	Germany	p	Scholar	paper	12	jar	draw WL	-0.110
Morawietz et al. (2024c)	26	42.31	undergrad	11.30	Germany	p	Scholar	paper	12	jar	draw WL	-0.312
Lasc et al. (2024)	171	43.86	pupils	6.81	USA	p	CitedRef	paper	11	jar	draw WL	0.278

Table 1. (*Continued.*)

Reference	*N*	Percent male	Sample type	Mean age	Participant origin	Pub	Source	Test mode	Items	Shape	Response format	*d*
Feraco (2025)	*45*	57.78	pupils	28.60	Italy	np	Author	screen	8	bottle	MC	*1.314*
Feraco (2025)	*45*	35.56	other	21.00	Italy	np	Author	screen	8	bottle	MC	*1.290*
Signorella (2025)	*121*	42.98	undergrad	NA	USA	np	Author	paper	1	bottle	draw WL	*0.521*

Note. Undergrad = undergraduate students; Pub = publication status (p = published; np = not published); Source = data source (Pietschnig = Pietschnig & Voracek, 2011; Scholar = Google Scholar; WoS = Web of Science; CitedRef = forward citation search of previous meta-analyses; Author = unpublished data sent by the author); paper = stimuli presented on paper; screen = stimuli presented on a screen; photo = stimuli were photos; real vessel = stimuli were models; NA = information not available.

Figure 11. *Forest Plot of Random-Effects Meta-Analysis.*

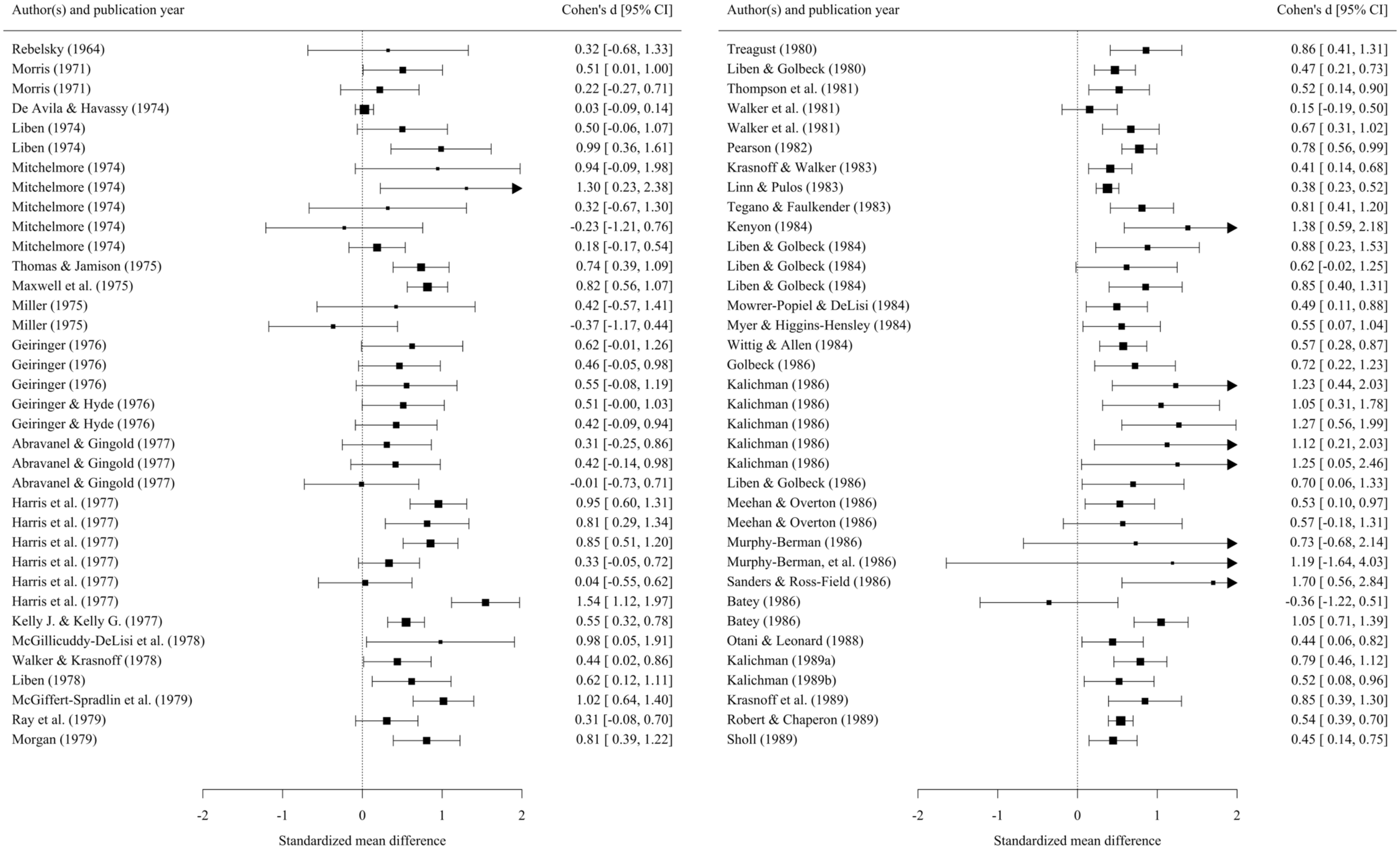


Figure 11. (*Continued*).

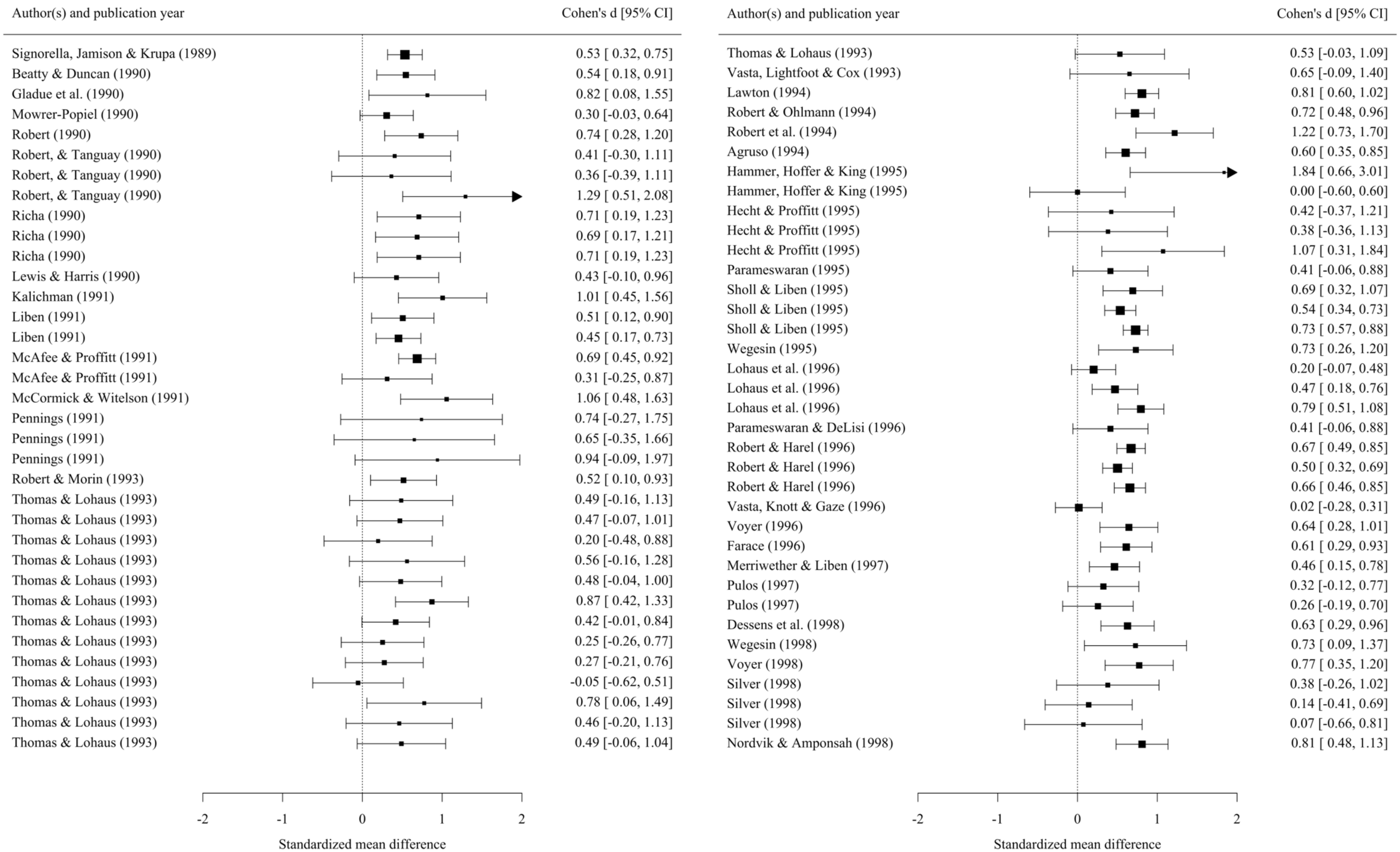
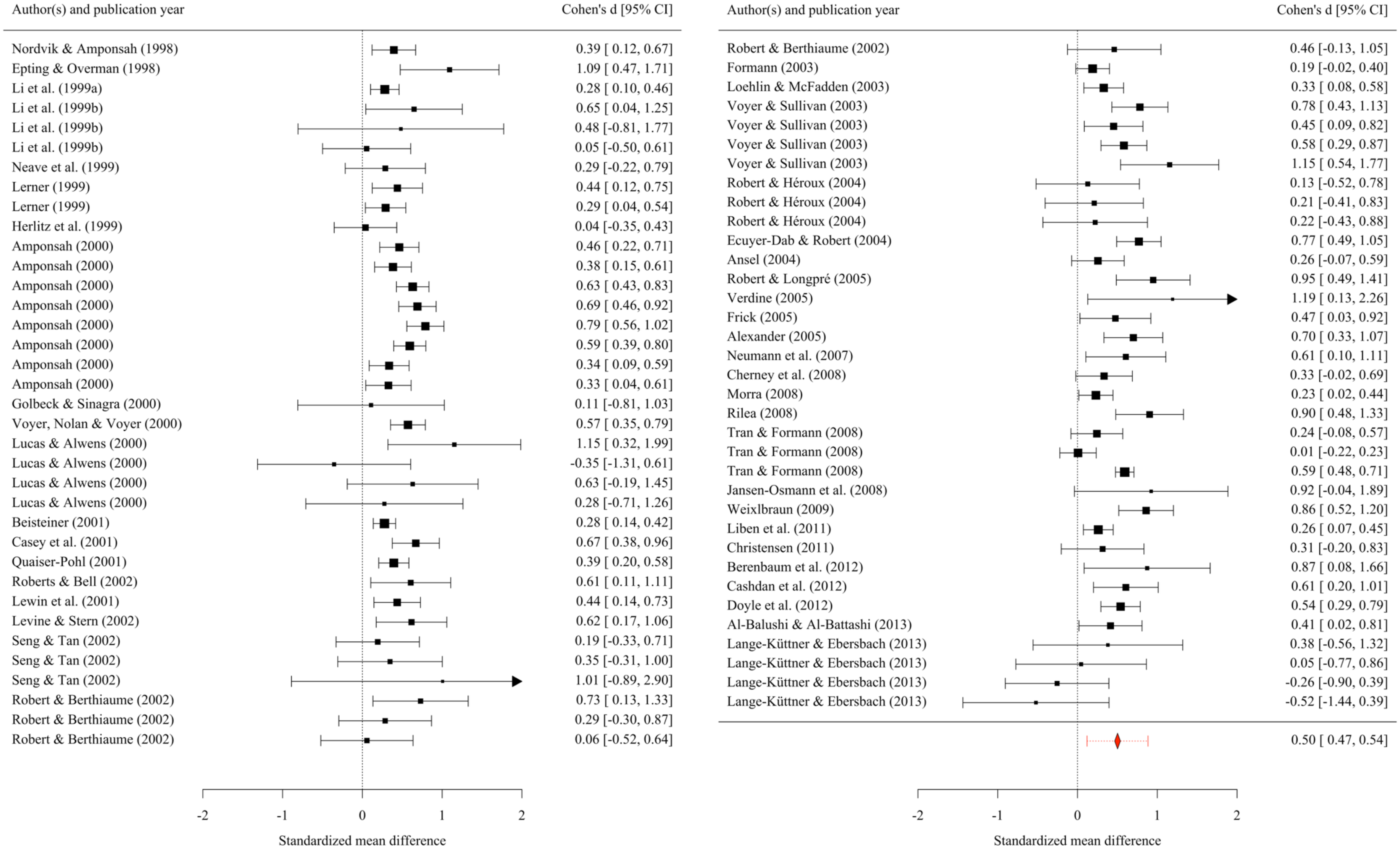


Figure 11. (*Continued*).



Moderator Analyses

Subgroup Analyses

To assess differences in effect sizes of sex differences in WLT performance according to various test- and sample characteristics, a series of subgroup analyses using mixed effects models was performed (see Table 2 for descriptive statistics of the respective summary effects).

Test Characteristics. Within all subsets formed according to differences regarding which WLT version was used and how it was administered, moderately sized positive effects, indicating sex differences in favor of male participants, were observed. These effects generalized across differences in response format (i.e., draw WL vs. MC vs. adjust WL; $Q(2) = 4.52$, $p = .132$), test setting (i.e., group vs. individual test; $Q(1) = 0.03$, $p = .860$), publication status ($Q(1) = 0.545$, $p = .461$), presence of a horizontal reference line ($Q(1) = 1.29$, $p = .256$), sex of first author ($Q(1) = 0.054$, $p = .816$), mode of stimulus presentation (i.e., drawn on paper vs. depicted on a screen vs. with a photograph of a vessel vs. with a model of a real vessel; $Q(3) = 1.37$, $p = .713$), and the presence of a time limit (i.e., power vs. speed test; $Q(1) = 0.019$, $p = .891$).

Effect sizes varied significantly depending on the vessel shape used (i.e., rectangular vs. cylindrical vs. Florence flask vs. bottle vs. jar vs. cup vs. mixed shapes; $Q(5) = 13.56$, $p = .019$). Pairwise comparisons revealed that this overall effect was solely driven by the mixed category, which yielded numerically larger sex differences compared to several specific shapes, including rectangles ($Q(1) = 6.17$, $p = .013$), bottles ($Q(1) = 6.94$, $p = .008$), Florence flasks ($Q(1) = 5.23$, $p = .022$), and jars ($Q(1) = 9.25$, $p = .002$). Pairwise comparisons among all other vessel shapes showed no nominally significant differences in effect sizes (all $Q(1)$s $\leqq$ 2.70, all ps $\geqq$ .1000).

Sample Characteristics. The observed meta-analytical summary effect was differentiated according to age group (i.e., children vs. adolescents vs. adults; $Q(2) = 25.18$, $p < .001$). Pairwise comparisons indicated that effect sizes were larger in adults than in children ($Q(1) = 21.13$, $p < .001$) and adolescents ($Q(1) = 13.00$, $p < .001$), whereas no nominally significant difference was found between children and adolescents ($Q(1) = 0.44$, $p = .507$). Beyond these age effects, sex differences generalized across several sample compositions. Moderately sized sex differences with male advantages were observed regardless of the continent of origin (i.e., North America vs. Europe vs. Asia vs. Africa vs. Australia; $Q(4) = 6.96$, $p = .138$) and the type of the sample tested (i.e., undergraduate students vs. pupils vs. general population vs. healthy control group vs. other; $Q(4) = 6.64$, $p = .156$).

Table 2. *Results of Overall and Subgroup Analyses.*

	Summary Effect (d)	SE	95% CI	p-value	Q	I^2 (%)
Overall (k = 261)	0.502	0.018	[0.470, 0.538]	< .0001	595.841***	53.12
			Response format			
draw WL (k = 211)	0.481	0.021	[0.441, 0.522]	< .0001	460.605***	51.31
MC (k = 39)	0.580	0.052	[0.478, 0.682]	< .0001	115.824***	72.24
Adjust WL (k = 10)	0.571	0.086	[0.402, 0.740]	< .0001	1.929	0.00
			Test setting			
Group (k = 118)	0.520	0.027	[0.468, 0.572]	<.0001	312.957***	59.23
Individual (k = 99)	0.527	0.032	[0.465, 0.590]	<.0001	158.396***	35.85
			Publication Status			
Published (k = 224)	0.497	0.019	[0.459, 0.534]	< .0001	491.129***	51.74
Unpublished (k = 43)	0.540	0.059	[0.425, 0.655]	< .0001	104.639***	61.06
			Horizontal reference line			
Provided (k = 148)	0.463	0.026	[0.412, 0.514]	< .0001	326.700***	56.89
Not provided (k = 45)	0.530	0.034	[0.465, 0.596]	< .0001	66.319*	25.44
			Sex of first author			
Male (k = 117)	0.507	0.027	[0.454, 0.560]	< .0001	285.862***	54.22
Female (k = 143)	0.498	0.026	[0.468, 0.550]	< .0001	301.316***	54.84
			Shape of vessel			
Rectangular (k = 129)	0.506	0.026	[0.457, 0.556]	< .0001	296.507***	52.64
Cylindrical (k = 6)	0.572	0.109	[0.358, 0.785]	< .0001	11.920*	54.31
Florence flask (k = 12)	0.435	0.085	[0.268, 0.602]	< .0001	37.173***	68.41
Bottle (k = 31)	0.438	0.062	[0.318, 0.559]	< .0001	55.698**	40.68
Jar (k = 19)	0.375	0.079	[0.219, 0.531]	< .0001	33.990*	47.80
Cup (k = 5)	0.500	0.083	[0.338, 0.663]	< .0001	6.772	0.01
Mixed shapes (k = 47)	0.634	0.038	[0.549, 0.699]	< .0001	82.705***	43.93

Table 2. (*Continued.*)

	Summary Effect (*d*)	*SE*	95% CI	*p*-value	*Q*	I^2 (%)
			Presentation mode			
Paper (*k* = 229)	0.498	0.020	[0.459, 0.538]	< .0001	539.259***	56.14
Screen (*k* = 24)	0.517	0.058	[0.403, 0.631]	< .0001	38.536*	32.17
Photograph (*k* = 3)	0.591	0.539	[-0.464, 1.648]	.2726	7.531*	77.40
Real vessel (*k* = 9)	0.618	0.086	[0.450, 0.786]	< .0001	1.824	0.00
			Power vs speed test			
Power (*k* = 221)	0.507	0.020	[0.468, 0.546]	< .0001	487.973***	52.26
Speed (*k* = 39)	0.507	0.058	[0.400, 0.614]	< .0001	89.259***	62.30
			Sample origin			
North America (*k* = 169)	0.529	0.023	[0.485, 0.573]	<.0001	371.210***	49.23
Europe (*k* = 71)	0.428	0.035	[0.357, 0.496]	< .0001	140.078***	49.29
Asia (*k* = 10)	0.507	0.097	[0.317, 0.697]	< .0001	13.241	31.58
Africa (*k* = 8)	0.472	0.052	[0.370, 0.573]	< .0001	10.518	13.25
Australia (*k* = 2)	0.359	0.158	[0.023, 0.668]	.0229	1.512	33.88
			Sample type			
Undergraduates (*k* = 110)	0.569	0.021	[0.527, 0.610]	< .0001	164.201**	29.14
Pupils (*k* = 96)	0.397	0.033	[0.333, 0.462]	< .0001	213.208***	52.62
General population (*k* = 9)	0.417	0.108	[0.205, 0629]	.0001	43.451***	82.69
Healthy control group (*k* = 4)	0.574	0.240	[0.103, 1.045]	.0169	5.969	51.34
Other (*k* = 37)	0.499	0.055	[0.392, 0.606]	< .0001	62.588**	41.69

Table 2. (*Continued.*)

	Summary Effect (d)	SE	95% CI	p-value	Q	I^2 (%)
			Age group			
Children (k = 52)	0.361	0.045	[0.272, 0.450]	< .0001	93.668***	38.47
Adolescents (k = 56)	0.406	0.048	[0.311, 0.500]	< .0001	141.998***	64.35
Adults (k = 152)	0.575	0.020	[0.535, 0.615]	< .0001	251.002***	38.69

Note. SE = standard error; 95% CI = upper and lower bound of 95% confidence interval; Q = Cochran's Q test statistic for heterogeneity; I^2 = proportion of observed variation reflecting true heterogeneity.

* $p < .05$. ** $p < .01$. *** $p < .001$

Meta-Regressions

To assess continuous moderators, linear precision-weighted meta-regression models were computed. Inferential statistics of summary effects of these analyses are summarized in Table 3.

Mean participant age positively predicted effect sizes of sex differences in WLT performance (b = 0.007, R^2 = 15.01, p < .001), indicating increasing male advantages with age. Because the data comprised relatively few older samples (age range: 5.00 – 79.00, median = 17.82, inter quartile range: 11.30 to 21.36), with a median age of only 21.35 years within the adult participant group, an exploratory robustness check using Mahalonobis distance was conducted to identify the 20 percent most extreme cases regarding the age effect on sex differences. Re-estimating the model after omitting these cases yielded a slightly larger slope compared to the full model (b = 0.009, R^2 = 13.97, p = .004), indicating that the positive effect of age was not driven by multivariate outliers (see Fig. 12).

Moreover, publication year negatively predicted the magnitude of the sex effect (b = -0.005, R^2 = 8.06, p < .001), indicating diminishing effect sizes over time. Visual inspection of the cumulative forest plot of sex differences according to publication year confirmed this pattern (see Fig. S2 in Appendix H). Notably, effect declines only appeared from the mid 1980s, following an increase in effect magnitude during the first years after Rebelsky's (1964) initial finding of sex differences in WLT performance. To explore whether the overall cross-temporal decline varied according to participant age, a meta-regression including the interaction of publication year and mean age was conducted. The interaction term was positive and statistically significant (*b* < 0.01, *p* = .005), indicating stronger cross-temporal effect declines in younger participants compared to older test-takers. To further investigate this pattern, separate exploratory meta-regressions of effect sizes on publication year were computed for each age group, which indicated that effect declines were strongest in adolescents (*b* = -0.011, R^2 = 27.57, *p* = .001; see Fig. 13) and weakest in adults (*b* = -0.003, R^2 = 10.91, *p* = .022). Effect changes in children were negative but not statistically significant (*b* = -0.004, R^2 = 0.00, *p* = .117). Follow-up interaction models testing pairwise differences in the slopes of the cross-temporal trends across age groups showed that the effect decline was significantly steeper in adolescents than in adults (*b* = 0.007, *p* = .030), while the slope differences between children and adolescents and between children and adults failed to reach nominal statistical significance (*b*s = -0.007 and 0.001; *p*s = .103 and .797, respectively).

Consistent with this pattern, a meta-regression of effect sizes on mean participant birth year yielded a significant negative effect (*b* = -0.005, R^2 = 10.52%, *p* < .001), suggesting smaller sex differences in more recent birth cohorts.

Finally, the number of test items administered did not significantly predict sex differences in WLT performance (*b* = 0.001, R^2 = 0.15, *p* = .351).

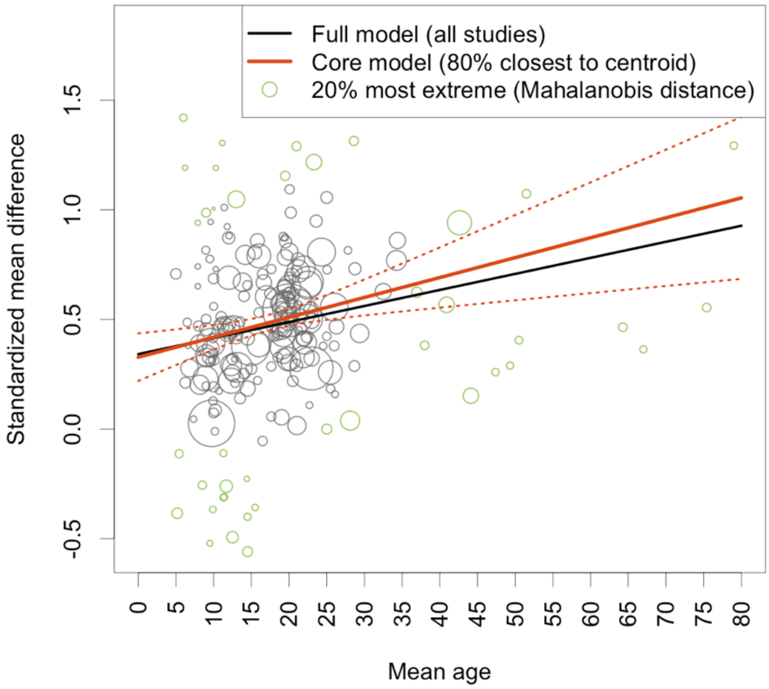
Table 3. *Results of Linear Precision-Weighted Meta-Regression Analyses*

	b (SE)	95% CI	*p*-value	R^2 (%)	*Q*	I^2 (%)
Mean age	0.007	[0.003, 0.011]	< .001	15.01	12.813***	42.81
Publication year	-0.005	[-0.008, -0.003]	< .001	8.06	15.494***	50.87
Birth year	-0.005	[-0.007, -0.002]	< .001	10.52	14.288***	44.42
Number of items	0.001	[-0.001, 0.003]	.351	0.15	0.870	52.92

Note. *SE* = standard error; 95% CI = upper and lower bound of 95% confidence interval; Q = Cochran's Q test statistic for heterogeneity; I^2 = proportion of observed variation reflecting true heterogeneity.

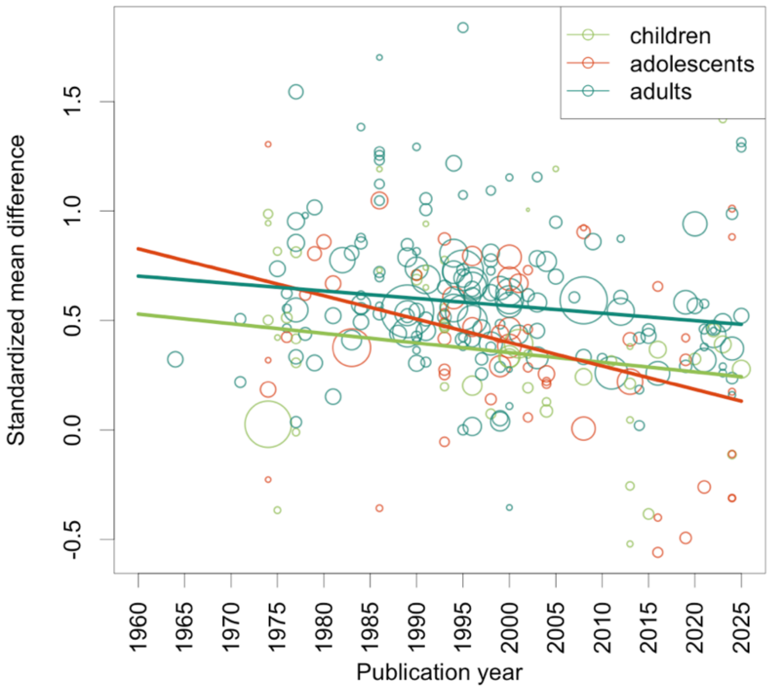
** *p* < .01. *** *p* < .001

Figure 12. *Precision-Weighted Meta-Regression of Participant Age.*



Note. The 20 percent most extreme cases (i.e., furthest from the cluster centroid) in the joint distribution of mean participant age and sex differences in WLT performance were identified using Mahalonobis distance. Larger bubbles represent larger sample sizes (i.e., higher precision).

Figure 13. *Precision-Weighted Meta-Regression of Publication Year.*



Note. Larger bubbles represent larger sample sizes (i.e., higher precision), scaled relative to the maximum sample size across all age groups.

Dissemination Bias

Only effects derived from published studies were included in analyses of dissemination bias ($k = 224$). Numerical outcomes of all bias detection methods are summarized in Table 4.

In *p*-curve, *p*-uniform, and *p*-uniform* analyses, 128 published and statistically significant effects were included. *p*-curve analysis yielded a right-skewed *p*-value distribution, which consisted of considerably more small than large (i.e., closer to .01 than .05) *p*-values. Moreover, binomial and continuous tests for half and full *p*-curves yielded no evidence for *p*-hacking (i.e., no evidence for inadequate evidential value; all *p*s < .0001) and suggested sufficient primary study power to indicate evidential value of observed effects (all *p*s > .9999; see Fig. 14). Results from *p*-uniform and *p*-uniform* did not indicate dissemination bias ($z = -2.316$, $p = .990$ and $z = 0.124$, $p = .940$, respectively). Whereas *p*-uniform* yielded a similar effect size estimate compared to the observed meta-analytical summary effect ($d = 0.51$), the adjusted estimate derived from *p*-uniform was slightly larger ($d = 0.57$).

Visual examination of the contour- and power-enhanced funnel plots (see Fig. 12) did not reveal meaningful signs of asymmetry. In line with this interpretation, neither Sterne and Egger's regression ($z = 0.535$, $p = .593$; see regression line in Fig. 15, Panel A), nor the rank correlation test (Kendall's $\tau = -0.009$, $p = .838$), suggested funnel plot asymmetry. Results of PET-PEESE confirmed these findings, yielding a 4% difference between the observed summary effect and the PEESE-based adjusted estimate, therefore not indicating confounding dissemination bias. Accordingly, although trim-and-fill yielded two missing studies on the left side of the funnel plot, the difference between the adjusted estimate and the observed meta-analytic summary effect amounted to less than 1%, thus not reaching the threshold of bias indication (Siegel et al., 2022). While no substantial evidence of funnel plot asymmetry was found, many included studies did not reach desirable levels of statistical power, yielding a median power estimate of 53.4% (see Fig. 15, Panel B). However, the test of excess significance did not provide evidence for dissemination bias, with 136 nominally significant studies expected, considering their assumed power, and 128 significant studies observed ($p_{TES} = .245$).

Finally, all moderate or severe selection models based on one- or two-tailed tests did not indicate bias (all differences between unadjusted and adjusted estimates ≦ 18%).

In all, none of the bias detection approaches reached the thresholds of bias indication specified by Siegel et al. (2022). Therefore, the triangulation of methods applied here clearly indicates a negligible effect of confounding dissemination bias on the observed meta-analytical findings.

Table 4. *Numerical Outcomes of Dissemination Bias Analyses.*

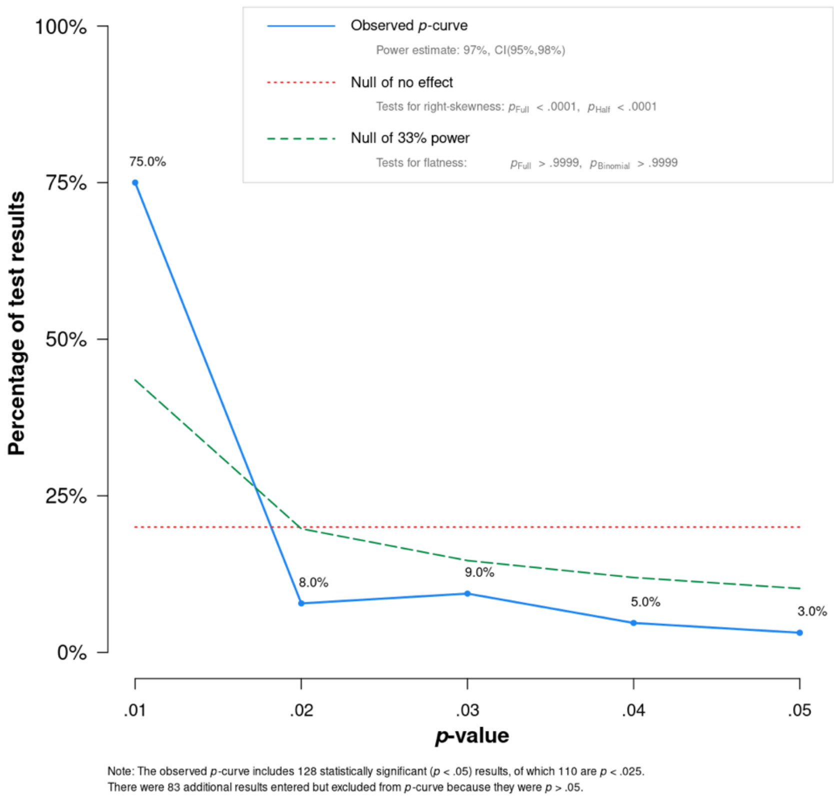
	Outcome	Threshold for bias indication	Bias indicated
p-curve	Half *p*-curve: $p < .0001$ (evidential value) $p > .9999$ (*p*-hacking) Full *p*-curve: $p < .0001$ (evidential value) $p > .9999$ (*p*-hacking)	*p*-value of half *p*-curve > .05 or *p*-values of both half and full *p*-curves > .10	No
p-uniform	$z = -2.316$ $p = .990$	$p < .10$	No
p-uniform*	$z = 0.124$ $p = .940$	$p < .10$	No
Sterne & Egger's regression	$z = 0.535$ $p = .593$	$p < .10$	No
Trim-And-Fill	unadjusted estimate = 0.496 adjusted estimate = 0.494 percent change = < 1%	Difference between meta-analytic summary effect and adjusted estimate exceeds 20% of meta-analytic summary effect in either direction	No
Selection Models		Difference between meta-analytic summary effect and adjusted estimate exceeds 20% of meta-analytic summary effect in either direction	
Moderate model, one-tailed	unadjusted estimate = 0.502 adjusted estimate = 0.469 percent change = 7%		No
Severe model, one-tailed	unadjusted estimate = 0.502 adjusted estimate = 0.411 percent change = 18%		No
Moderate model, two-tailed	unadjusted estimate = 0.502 adjusted estimate = 0.477 percent change = 5%		No
Severe model, two-tailed	unadjusted estimate = 0.502 adjusted estimate = 0.441 percent change = 12%		No
Rank correlation test	$\tau = -0.009$ $p = .838$	$p < .10$	No

Table 4. (*Continued*).

	Outcome	Threshold for bias indication	Bias indicated
PET-PEESE	PET: intercept = 0.475 $p < .0001$ PEESE: unadjusted estimate = 0.502 adjusted estimate = 0.482 percent change = 4%	Difference between meta-analytic summary effect and adjusted estimate exceeds 20% of meta-analytic summary effect in either direction; if PET estimate is significant at $p < .10$, PEESE intercept is interpreted as adjusted estimate	No
Test of excess significance	expected: 136 observed: 128 p = .245	p < .10 and observed number of significant findings (O) exceeds expected number of significant findings	No

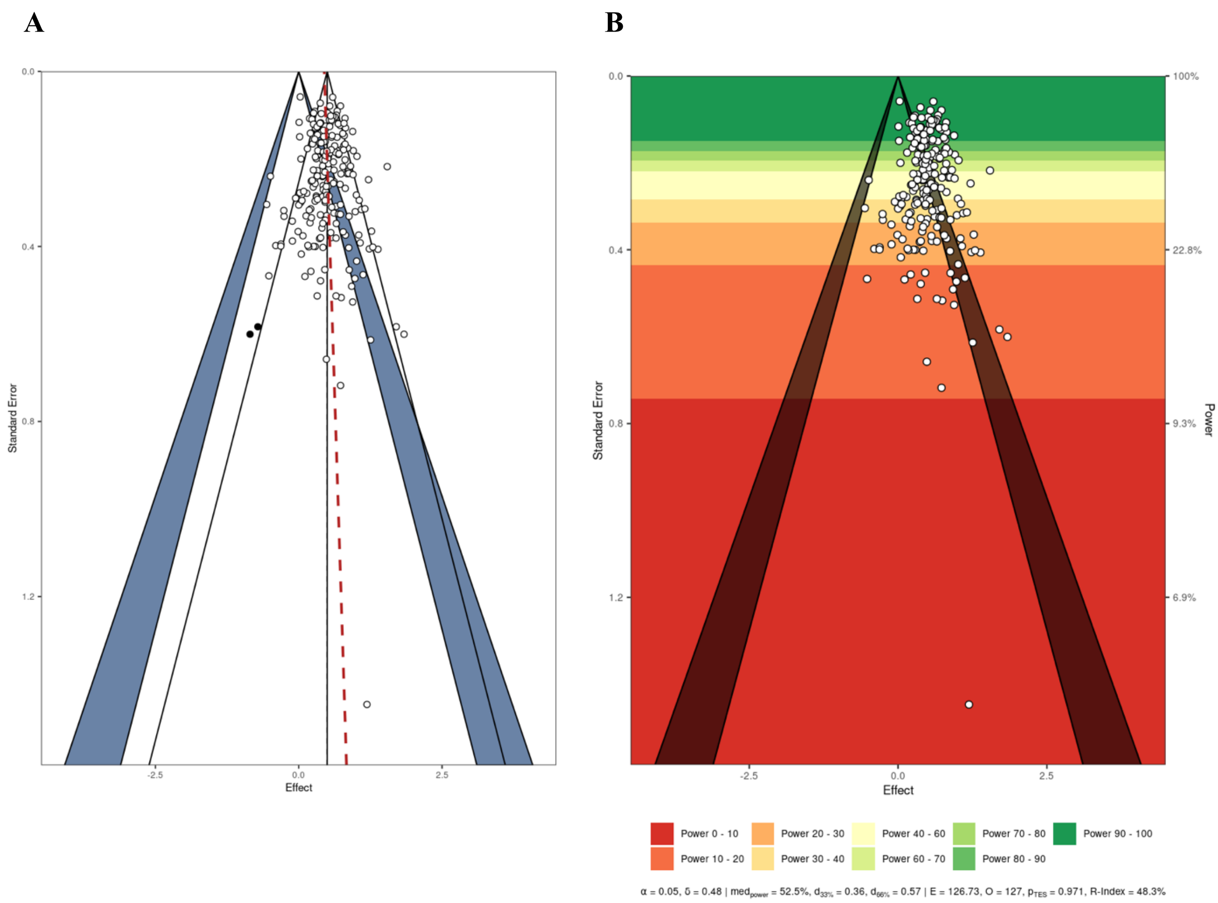
Note. Thresholds according to Siegel et al. (2022) are used as inference criteria for bias indication; PET-PEESE = precision-effect test and precision-effect estimate with standard errors.

Figure 14. *P-Curve Plot.*



Note. The figure shows the distribution of p-values of significant ($\alpha < .05$) published findings.

Figure 15. *Contour- and Power-Enhanced Funnel Plots.*



Note. Panel **A**: Contour-enhanced funnel plot of published effect sizes. The vertical solid line depicts the observed meta-analytical summary effect; black dots represent studies imputed by the trim-and-fill method; white dots represent the observed effect sizes; the red dashed line depicts Egger’s regression line; effect sizes in the blue areas are significant at $p < .05$, effect sizes outside the blue areas are significant at $p < .01$.

Panel **B**: Power-enhanced funnel plot of published effect sizes; warmer colors represent lower and colder colors represent higher primary study power; effect sizes in the dark grey areas are significant at $p < .05$, effect sizes outside the dark grey areas are significant at $p < .01$; at the bottom of the plot, information on the significance level and fixed-effect estimate used for power estimations, median power of primary studies, the true effect size necessary for achieving statistical power of 33% and 66%, respectively, results of the test of excess significance, and the R-index indicating expected replicability of the observed findings is provided.

Multiverse Meta-Analyses

Specification Curve and Multiverse Meta-Analyses

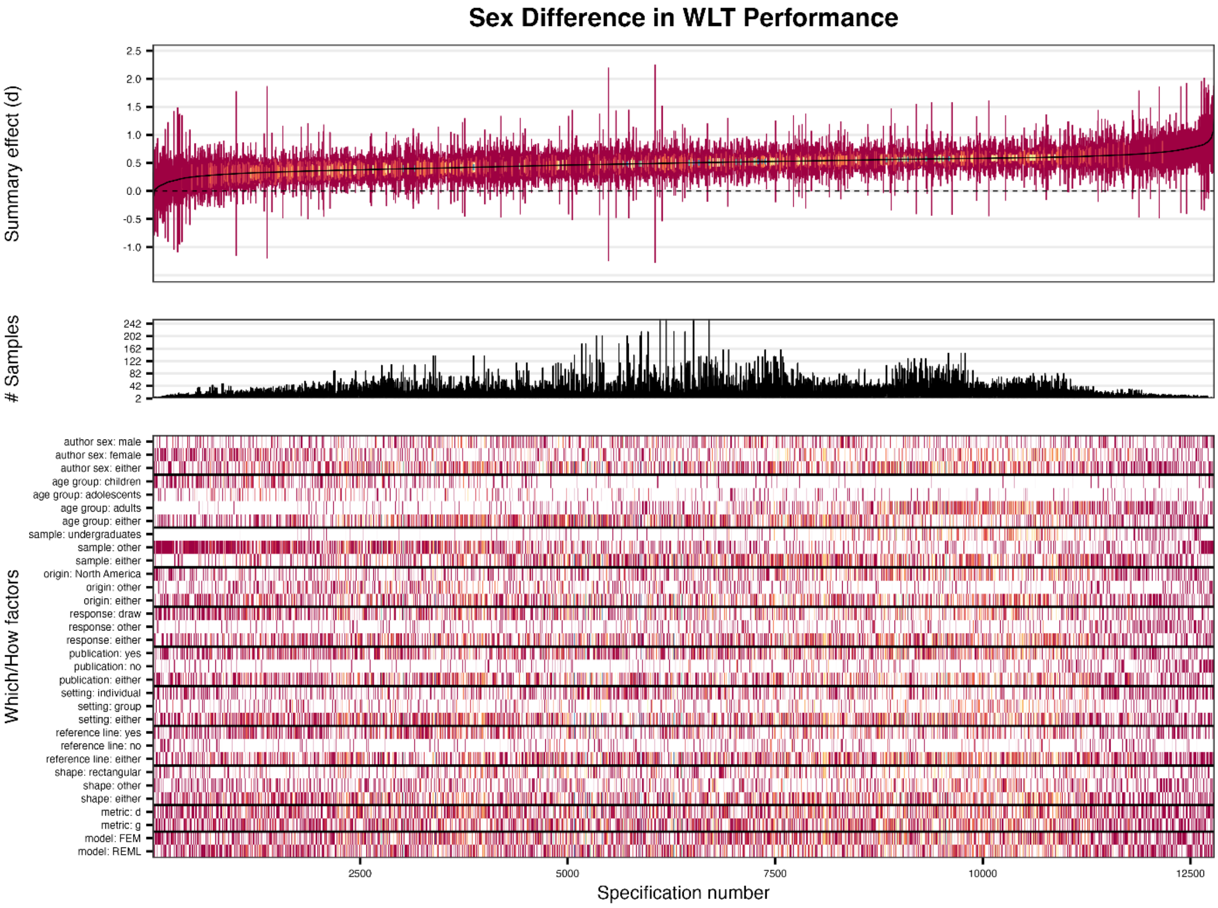
Almost all reasonable combinations of *which* and *how* factors yielded a positive summary effect, indicating sex difference in favor of men. More specifically, 12,276 out of the 12,996 summary effects (i.e., 94%) were positive and nominally significant ($p < .05$). Effect sizes ranged from a minimum of $d = -0.25$ to a maximum of $d = 1.34$, with an average of $d = 0.48$ and a median of $d = 0.50$. None of the specifications yielded a nominally significant negative or null effect. As Figure 16 illustrates, most specifications resulted in summary effects sized around $d = 0.50$ (inter quartile d range: 0.40 to 0.57), whereas these specifications yielded more precise estimates (i.e., effects with narrower confidence intervals) compared to effects at the lower and upper ends of the effect size distribution. The observed descriptive meta-analytic specification curve deviated substantially from the under-the-null scenario of a nil-effect simulated using parametric bootstrapping (see Fig. 17). These findings underline the remarkable generality of the observed meta-analytic summary effect.

Figure 18 displays a histogram of the p-value distribution for the summary effects of all meta-analytic specifications, used to visualize the results of the multiverse approach adopted for meta-analysis (Voracek et al., 2019). The proportion of nominally significant findings amounted to 94%, which further supports the robustness of the above evidence.

Combinatorial Meta-Analysis

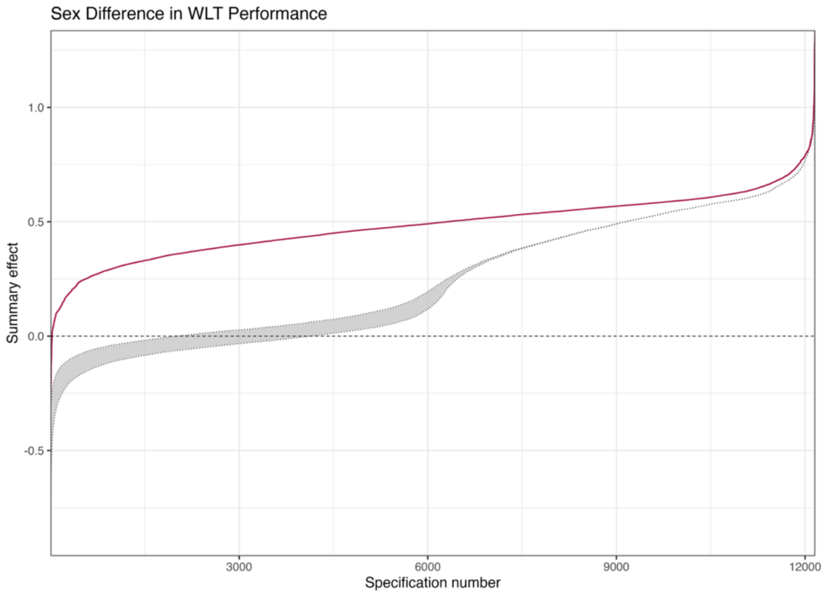
Visual inspection of the GOSH plot did not indicate substantial deviations for the majority of the 100,000 random subsets of all possible combinations from the results obtained with standard and specification curve meta-analyses (see Fig. 19). Specifically, summary effects averaged $d = 0.49$ (median $d = 0.48$, inter quartile d range: 0.47 to 0.50). Between-studies heterogeneity was small to moderate in most of the random subsets, averaging $I^2 = 52.51$ (median $I^2 = 55.07$, inter quartile range: 49.44 to 57.88). In subsets that included at least one of the leverage points identified using influence diagnostics, neither summary effects nor effect heterogeneity substantially deviated from the estimates obtained in subsets excluding these outliers. These findings further underline the generality of the observed sex differences.

Figure 16. *Descriptive Meta-Analytic Specification Curve Plot.*



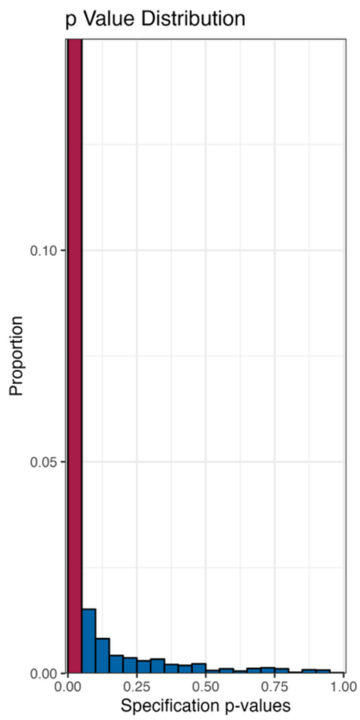
Note. Meta-analytic summary effects along with their 95% confidence intervals are illustrated in the top panel, sorted by magnitude. An overlap of confidence intervals with the dotted line represents a nominally non-significant summary effect. The number of samples within the respective specification is represented in the middle panel. The bottom panel includes the combination of Which and How factors that defines each specification. The colors in this panel represent the number of samples included in each specification, with colder and warmer colors indicating higher and lower precision, respectively.

Figure 17. *Inferential Meta-Analytic Specification Curve Plot.*



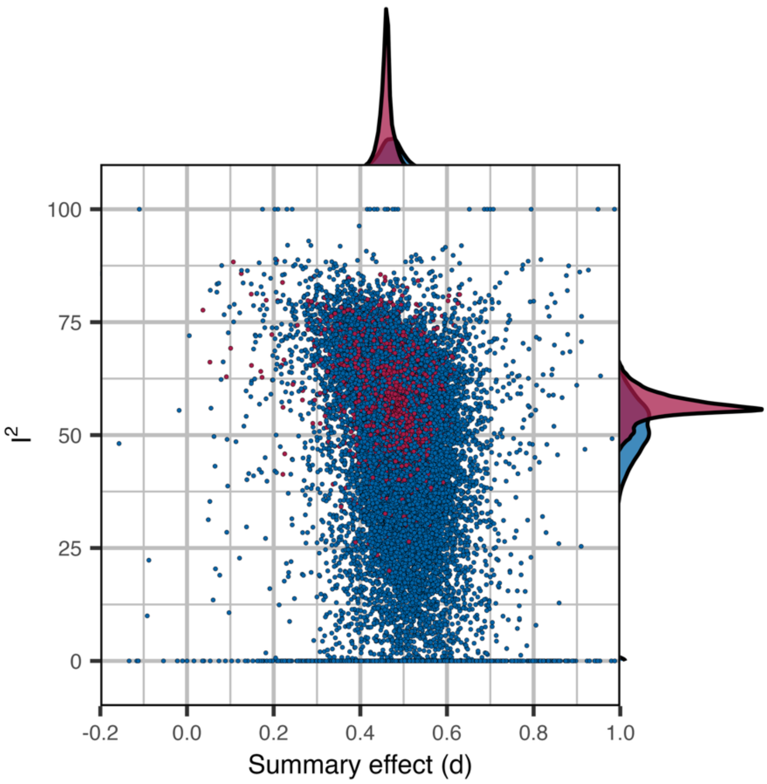
Note. The solid red line depicts the specification curve of the observed meta-analytical summary effects sorted by magnitude. The limits of the grey area represent the upper and lower bounds of the 95% confidence interval of 1,000 specification curves simulated under the under-the-null scenario of a nil-effect using parametric bootstrapping.

Figure 18. *Histogram of the p-Value Distribution for All Meta-Analytic Specifications.*



Note. The leftmost column (red) represents the proportion of nominally significant effects ($p < .05$).

Figure 19. *GOSH Plot for Combinatorial Meta-Analysis.*



Note. The dots represent the summary effects of 100,000 random subsets of all possible combinations. Estimates from subsets including at least one of the leverage points identified with influence diagnostics are highlighted in red.

Discussion

The present study provides evidence for remarkably robust, moderately sized sex difference in WLT performance, favoring men. This effect generalized across the great majority of variations regarding the sample tested, the WLT version administered, and the meta-analytical model characteristics chosen. The sex differences averaged $d = 0.50$ in the standard meta-analysis as well as $d = 0.49$ in specification curve and combinatorial meta-analyses. However, effect sizes were differentiated according to participant age and declined slightly over time. Several points of interest raised by these key findings are discussed below.

Comparison With Previous Meta-Analyses

Meta-Analytical Summary Effects

The direction and magnitude ($d \approx 0.50$) of the meta-analytical summary effect observed in the present analyses as well as its substantial generality are largely consistent with findings from prior quantitative syntheses of sex differences in WLT performance. Previous meta-analyses similarly yielded male advantages of moderate magnitude, despite some variability in effect estimates and meta-analytical designs.

Early work by Linn and Petersen (1985) combined WLTs and the RFT as indicators of spatial perception and reported a summary effect size of $d = 0.44$, without providing a WLT-specific estimate. Similarly, Signorella and Jamison (1986) included WLTs as measures of spatial perception in their meta-analysis, but focused on associations between gender self-concept (i.e., masculinity–femininity) and spatial perception rather than estimating sex differences directly.

In contrast, Voyer et al. (1995) reported test-specific estimates of sex differences in 12 different measures of spatial ability, including WLTs. Based on 62 primary study effects, their meta-analysis yielded male advantages in WLT performance amounting to $d = 0.42$. The thus far most recent meta-analysis by Pietschnig and Voracek (2011), which incorporated 157 effects, resulted in a summary effect of $d = 0.55$. Drawing on a substantially expanded database of 267 independent samples, the presently observed effect size estimate falls between these earlier findings, indicating sex differences in favor of men amounting to half a standard deviation.

Effects Related to Participant Age

The observed meta-analytical summary effect was moderated by mean age in the present analysis. This finding aligns with previous meta-analytical evidence, consistently demonstrating larger effect sizes in older participants (Linn & Petersen, 1985; Pietschnig & Voracek, 2011; Voyer et al., 1995). The results of Linn and Petersen (1985) showed that sex differences in spatial perception were only statistically significant for participants older than 18 years but not for under-18-year-olds. Conversely, Voyer et al. (1995) and Pietschnig and Voracek (2011) reported that sex differences already existed in children with boys performing better than girls and significantly increased with age. The present research supports these claims, as the observed sex differences increased from small effect size in childhood (d = 0.36) to medium effect size in adolescence and adulthood (d = 0.41 and d = 0.58, respectively).

An exploratory analysis using Mahalonobis distance showed that this age effect was not driven by outliers. Nevertheless, predictions regarding effect size trends at higher age are constrained based on the available evidence, as adult samples were, on average, relatively young due to a marked underrepresentation of older participants. Specifically, only 12 of the 268 primary study effects (i.e., less than 5%) derived from samples with a mean age above 40 years (Coté & Lalumière, 2020; Geiringer, 1976; Hecht & Proffitt, 1995; Robert & Tanguay, 1990; Tomai et al., 2024; Tran & Formann, 2008; Walker et al., 1981).

For example, Robert and Tanguay (1990) examined WLT sex differences among teachers aged 40 to 61, 62 to 72, and 73 to 84. While effects were small in the two younger groups, sex differences in elderly participants reached very large effect size. In contrast, Geiringer (1976) compared middle-aged (50 to 55 years), young elderly (60 to 69 years), and mature elderly (70 to 89 years) participants and reported moderate male advantages for all three groups, with effect sizes peaking in the middle-aged group. Tran and Formann (2008) provided the only study spanning a comparably broad age range of 4 to 95 years, reported small sex differences in young and middle age and moderate effects in participants above 60 years of age.

Given the heterogeneity of these findings, further research incorporating samples of older adults is needed to better understand how effect sizes of sex differences in WLT performance evolve across advanced age.

Whilst effect size changes in later adulthood require further clarification, the presently available data revealed a robust age-related increase in effect magnitude. This pattern may be interpreted within the framework of the "bent twig" hypothesis (Robert & Harel; 1996; Vasta

& Liben, 1996). Originally proposed by Sherman (1967) to explain female superiority in memory and language performance, the theory provides an integrative approach for explaining the emergence of sex differences in cognitive abilities. Differential peri- and post-natal endocrinal and neurobiological mechanisms are assumed to inform a sex-specific pre-disposition for certain preferences and abilities that are then magnified through psycho-social mechanisms and differential experiences (Halpern, 2013).

Regarding WLT performance specifically and spatial ability more broadly, boys may, on average, show a stronger biologically influenced tendency than girls to engage in spatial activities in early age (Ceci et al., 2009; Todd et al., 2017). These preferences may then be amplified through environmental influences such as gendered toy play (e.g., dolls for girls vs. building blocks for boys) explicitly or implicitly encouraged by parents (Liben et al., 2018; Kollmayer et al., 2018b). Consistent with this account, adults reporting a preference for non-spatial toys and activities during their childhood have been found to exhibit lower WLT performance (Doyle et al., 2012) and larger WLT-based sex differences (Voyer et al., 2000) compared to individuals who preferred spatial forms of play. As children enter school age, stereotypes regarding interest and performance in different subjects (e.g., languages and arts for girls vs. science and mathematics for boys) conveyed in educational contexts may further reinforce differential engagement in spatial activities between boys and girls (Kollmayer et al., 2018a). Considering that sex differences showed a particularly pronounced cross-temporal decline among adolescents in the present research, it is conceivable that such educational socialization practices have become less differentiated across cohorts in more recent decades.

Moreover, additional psychosocial factors such as sex role identity (Kelly & Beltz, 2022), spatial self-concepts, i.e., beliefs about one's own spatial skills (Signorella & Liben, 2024), spatial confidence, i.e., self-confidence when solving spatial tasks (Nardi et al., 2013), spatial anxiety, i.e., nervousness when engaging in spatial thinking (Geer, 2019; Geer et al., 2024), and stereotype threat, i.e., negative stereotypes about women's spatial skills (Doyle & Voyer, 2016) may gain particular relevance during the progression through adolescence and young adulthood, thereby further driving divergences in spatial engagement and performance.

Overall, according to the "bent twig" hypothesis, the small sex differences found in children may be attributed to a biologically influenced tendency that is gradually accentuated through psychosocial factors, resulting in increasingly pronounced sex differences in WLT performance with increasing age.

Effect Size Changes Over Time

Weighted meta-regressions showed that effect sizes were negatively related to both publication year and mean participant birth year, indicating a decline in the magnitude of sex differences over time. Whereas these findings contrast with Pietschnig & Voracek's (2011) assumption of cross-temporal stability of the observed sex differences, they align with the results of Voyer et al. (1995). In their analyses, Voyer et al. focused on birth year rather than publication year in order to investigate cohort-related influences. They found smaller sex differences in more recent birth cohorts and interpreted this effect decline as a potential consequence of changes in sex-related societal attitudes and educational practices. Accordingly, previous research has highlighted the role of educational measures in shaping more egalitarian gender role attitudes in adolescents across cultural contexts (e.g., Dhar et al., 2022; Du et al., 2021; Kågesten et al., 2016). Moreover, more egalitarian gender role attitudes in adolescence have been linked to smaller sex differences in mathematics performance (Taraszow et al., 2024), which is moderately associated with spatial skills (Atit et al., 2022). Against this background, the present analyses yielded larger effect declines in adolescents than in adults and children.

The present findings further align with recent evidence demonstrating declining effect magnitudes over time in research on cognitive abilities (Pietschnig et al., 2019) and in other psychological domains. Such decline effects have previously been attributed to an abundance of underpowered studies, publication bias, and selective reporting in the time period following the initial publication of a finding (Protzko & Schooler, 2017). Of note, in the present work, none of the applied bias detection methods provided evidence for publication bias, multiverse analyses demonstrated substantial generality of the meta-analytical summary effect, and cumulative meta-analysis revealed that effect declines occurred only after initial effect increases after Rebelsky (1964) first reported sex differences in WLT performance.

Taken together, these findings suggest that cross-temporal declines in effect magnitudes likely reflect genuine cohort-related change rather than arising primarily from methodological artifacts. Further research is however needed to elucidate the mechanisms underlying the observed attenuation of sex differences over time, while taking into account potential methodological issues such as low statistical power and publication bias.

Relevance of the Present Findings

Male Advantages in Visual Processing

The results of the specification curve, multiverse, and combinatorial meta-analyses attested to the remarkable generality of sex differences in favor of men in WLT performance across procedural and analytical specifications, pointing to a male advantage in spatial perception (i.e., extrinsic-static spatial skills) more generally (Linn & Petersen, 1985; Newcombe & Shipley, 2014), and *Frame of Reference Illusions* more specifically (Buckley et al., 2018; McNeal et al., 2024). This is consistent with a recent review by Reynolds et al. (2022), who found no substantial evidence for reliable sex differences in general intelligence but instead identified meaningful divergences in specific cognitive abilities, favoring men or women depending on the domain. Specifically, female advantages in latent processing speed conceptualized within the CHC theory have been reported consistently across studies, whereas, in line with the present results, male advantages have repeatedly been found for latent visual processing. Thus, the sex effect observed here is best understood as reflecting differences in domain-specific visual processing rather than domain-general cognitive ability.

Linking Spatial Cognition to Sex Differences in STEM Achievement

Given the early emergence and robustness of sex differences in WLT performance observed here, an important question concerns their relevance for downstream educational and occupational outcomes, particularly in STEM domains. Sex differences in spatial ability have been widely discussed within the context of attainment and achievement in STEM domains as one of many factors explaining the underrepresentation of women in science (Ceci et al., 2009; Reilly et al., 2017). A substantial body of research indicates that spatial abilities are associated with later mathematics performance and STEM-related educational pathways (Atit et al., 2022; Wai et al., 2009; Webb et al., 2007; Xie et al., 2025), including evidence from studies specifically employing Water Level Tasks (Scott et al., 2023; Voyer, 1998).

Against this background, early sex differences in spatial skills may contribute to the development of sex differences in mathematics and science (Ceci et al., 2009; Reilly et al., 2017). Consistent with this interpretation, the present meta-analytic results indicate that small but reliable sex differences in WLT performance are already observable in childhood, at ages when spatial abilities begin to predict later STEM-related outcomes (Frick, 2019; Gilligan et al., 2017). These early differences may therefore represent one of several developmental starting points that contribute to later sex differences in STEM achievement and interest.

The present findings further indicate that sex differences in WLT performance increase with age, raising important questions about the extent to which spatial training may attenuate sex differences in WLT performance and other spatial domains. In this vein, training studies have shown that performance in a wide range of spatial tasks can be improved through targeted interventions and experience, with men and women responding equally well to spatial training (Uttal et al., 2013a).

Moreover, some evidence suggests that spatial training may positively affect STEM attainment and achievement (Stieff & Uttal, 2015; Uttal & Cohen, 2013). These findings have led researchers to call for the integration of spatial training into educational practice (Gilligan-Lee et al. (2022); Lubinski, 2010; Newcombe & Frick, 2010). In addition, it has been discussed that spatial interventions may contribute to reduced sex differences in later spatial cognition and STEM performance when implemented in early development (Reilly et al., 2017). Accordingly, Newcombe and Frick (2010) have argued for the introduction of spatial instruction in early at-home and educational settings before the sex gap widens. The present finding of increasing sex differences in WLT performance with age is consistent with this perspective. At the same time, more robust evidence is needed to determine whether such training can effectively improve STEM outcomes (Stieff & Uttal, 2015) and meaningfully attenuate related sex differences (Newcombe, 2020; Uttal et al., 2013a) .

Beyond educational outcomes and training-related interventions, the present findings also have implications for understanding sex differences in spatial perception at higher levels of expertise. Performance on WLTs has been linked to expertise in several STEM fields and other spatially intensive domains, with experts consistently outperforming non-experts. However, consistent with the generality of the presently observed summary effect across various sample characteristics, sex differences favoring men persist even among expert populations (Feraco, 2025; Hecht & Proffitt, 1995; Kalichman, 1986; Nordvik & Amponsah, 1998; Pulos, 1997; Taufer, 2021; Tomai et al., 2024). Notably, in some studies, sex differences appeared to be descriptively, but nominally non-significantly, larger among experts than among non-experts (Feraco, 2025; Nordvik & Amponsah, 1998; Tomai et al., 2024), a pattern that has yet to be tested systematically but has already been shown in other spatial domains (Tsigeman et al., 2023).

Taken together, these findings imply that expertise in STEM and other spatially related domains, while linked to better spatial perception relative to non-experts, may not be sufficient to attenuate existing sex differences. This observation underscores the potential of implementing targeted spatial training within higher STEM education (Gagnier et al., 2016; Uttal & Cohen, 2013). However, further research is needed to better understand the influence of expertise on sex differences in spatial thinking, and to determine how these associations interact with spatial training and STEM achievement.

Limitations

Several limitations of the present research warrant consideration. First, measurement invariance across male and female participants was not accounted for in any of the included studies, which is essential to address to ensure fair and valid comparisons of test scores (Cheng, 2017; Navarro-González et al., 2024). Of note, the absence of formal tests of measurement invariance reflects a broader limitation of the existing WLT literature rather than a shortcoming specific to the present meta-analysis, whereas evidence from research employing other spatial tasks suggests that measurement non-invariance may not substantially limit the interpretability of sex differences in spatial cognition (e.g., Maeda & Yoon, 2015; Xu et al., 2016). Against this background, the observed generality of sex differences across a wide range of samples, task variants, and analytic specifications suggests that the main findings are unlikely to be solely attributable to differential item functioning. Importantly, future research should nonetheless assess measurement invariance of WLTs across sex and other demographic groups to strengthen the interpretability of group comparisons.

Second, 243 out of the 268 effect sizes included in the meta-analysis (i.e., 91%) originated from studies conducted in WEIRD countries, with 129 effects coming from the United States. This pronounced geographical selectivity may limit the applicability of the observed sex differences in WLT performance across cultural contexts. The scarce evidence from non-WERID studies has yielded mixed results. For example, Davis et al. (2021) reported a small female advantage among seminomadic pastoralist-forager children from northern Namibia, contrasting with the moderate male advantage found here. Moreover, Li et al. (1999a, 1999b) observed higher overall performance among Chinese compared to American students, although they found male advantages among both nationalities. However, as discussed above, measurement invariance needs to be established to allow for valid cross-cultural comparisons. Taken together, these findings warrant further research including non-WEIRD samples to allow for broader generalizability of meta-analytical results.

Third, substantial heterogeneity between effect sizes remained even after accounting for theoretically relevant moderators. This suggests that additional sources of variability in sex differences in WLT performance have yet to be fully identified. However, results from the present multiverse analyses indicate that the observed meta-analytical summary effect is stable across a wide range of (reasonable) specifications, supporting the robustness of the reported sex differences despite remaining unexplained variability.

Conclusion

The present meta-analysis provides evidence for moderately sized sex differences in Water Level Task performance favoring men. This effect generalized across a wide range of specifications regarding which data were included in the analysis and how meta-analytical examination was performed, with the large majority of specifications yielding a summary effect of approximately half a standard deviation. The observed sex differences appeared to be remarkably robust with respect to most potential moderators such as the shape of the vessel presented, the number of test items used, or the type of sample tested. Yet, effect sizes declined over time, pointing to potential methodological and/or contextual influences on their magnitude. Although Piaget and Inhelder (1948/1956) proposed that the emergence of an inner coordinate system during the concrete operational stage of cognitive development would enable all typically developing individuals to solve Water Level Tasks from middle childhood onward, the present findings suggest a more differentiated pattern. Sex differences were already observable in childhood, increased in magnitude with age, and persisted into adulthood, indicating that the concept of horizontality invariance may not emerge uniformly across individuals and, in some cases, may not fully develop even by adulthood. These results are consistent with previous evidence indicating male advantages in latent visual processing. As spatial cognition plays a meaningful role in educational pathways related to mathematics and science, the present findings highlight the potential relevance of early and persistent sex differences in spatial perception for later STEM attainment and achievement.

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Studies marked with an asterisk were included in the present-meta-analysis. Studies marked with two asterisks were included in both the meta-analysis by Pietschnig and Voracek (2011) and the present work.

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Appendix A

Abstracts in English and German

Abstract (English)

Nearly 80 years ago, Jean Piaget introduced the Water Level Task (WLT) to investigate emerging concepts of horizontality invariance in children, proposing that a universal ability to solve this task by about age nine reflects the progression through the concrete operational stage of cognitive development. However, subsequent research has shown substantial difficulties in solving WLTs even among adults, with men consistently outperforming women. While this sex difference has repeatedly been replicated, its generality and cross-temporal stability remain unclear. To address this gap, the present research synthesized all available evidence of sex differences in WLT performance from 1964 to 2025 (267 samples, totaling more than 38,000 participants) by means of preregistered random-effects meta-analyses. The stability of the meta-analytical summary effect across potential moderators was examined using subgroup analyses and precision-weighted meta-regressions. Moreover, meta-analytical specification curve analyses and a combinatorial meta-analysis were conducted to account for all reasonable and possible ways of which data to meta-analyze and how to meta-analyze them. Results showed moderately sized sex differences in WLT performance favoring men ($d = 0.50$; 95% CI [0.47, 0.54]) that increased with age but declined slightly over time. Multiverse analyses revealed remarkable generality of this effect across different sample characteristics, test variants, and meta-analytical decisions, with 12,276 out of 12,996 summary effect calculations (94%) yielding nominally significant male advantages, averaging $d = 0.49$. Taken together, these findings indicate moderate, robust, yet cross-temporally diminishing sex differences in WLT performance, challenging Piaget's notion of a universal understanding of horizontality invariance by late childhood.

Keywords: Water Level Task, Piaget, sex differences, meta-analysis, multiverse meta-analysis, specification curve, combinatorial meta-analysis.

Abstract (German)

Vor fast 80 Jahren entwickelte Jean Piaget den Water Level Task (WLT) als Mittel zur Untersuchung der Entwicklung von Horizontalitätsinvarianz bei Kindern. Er nahm an, dass die universelle Fähigkeit zur Lösung dieser Aufgabe den Fortschritt durch das konkret operationale Stadium kognitiver Entwicklung widerspiegelt. Nachfolgende Forschung zeigte jedoch sogar bei Erwachsenen erhebliche Probleme bei der Lösung von WLTs, wobei Frauen größere Schwierigkeiten zeigten als Männer. Obwohl dieser Geschlechtsunterschied wiederholt repliziert wurde, sind seine Allgemeingültigkeit sowie seine zeitliche Stabilität bisher unzureichend geklärt. In der vorliegenden Studie wurde daher sämtliche verfügbare Evidenz zu Geschlechtsunterschieden in der WLT-Leistung von 1964 bis 2025 (267 Stichproben mit insgesamt mehr als 38,000 Versuchspersonen) mittels präregistrierter Random-Effects-Metaanalysen synthetisiert. Die Stabilität des meta-analytischen Gesamteffekts über potenzielle Moderatoren hinweg wurde anhand von Subgruppenanalysen und präzisionsgewichteten Metaregressionsmodellen untersucht. Darüber hinaus wurden durch metaanalytische Spezifikationskurvenanalysen und kombinatorische Metaanalysen alle sinnvollen sowie möglichen Variationen der Datenselektion und der meta-analytischen Modellierung berücksichtigt. Die Ergebnisse zeigten moderate Geschlechtsunterschiede in der WLT-Leistung zugunsten von Männern (d = 0.50; 95% CI [0.47, 0.54]), welche mit dem Alter anstiegen, jedoch über die Zeit leicht abnahmen. Multiversum-Analysen deuteten eine bemerkenswerte Generalisierbarkeit dieses Effekts über verschiedene Stichprobenmerkmale, Testvarianten und meta-analytische Entscheidungen hinweg an, wobei 12,276 der 12,996 Metaanalysen (94%) statistisch signifikante Geschlechtsunterschiede zugunsten von Männern mit einem durchschnittlichen Gesamteffekt von d = 0.49 ergaben. Insgesamt weisen diese Ergebnisse auf moderate, robuste, aber über die Zeit sinkende Geschlechtsunterschiede in der WLT-Leistung hin und stellen somit Piagets Annahme eines universellen Verständnisses der Horizontalitätsinvarianz bis zum späten Kindesalter infrage.

Schlüsselwörter: Water Level Task, Piaget, Geschlechtsunterschiede, Metaanalyse, Multiversum Metaanalyse, Spezifikationskurve, kombinatorische Metaanalyse.

Appendix B

Deviations From the Pre-Registration Protocol

Table S1 presents descriptions and justifications of deviations from the preregistration (available at https://osf.io/zdwfh/overview).

Table S1. *Deviations from Pre-Registration.*

Deviation	Rationale
Effect sizes were interpreted according to the benchmarks proposed by Funder and Ozer (2019) with absolute *d* = 0.10, 0.20, 0.41, 0.63, and 0.87 as bottom thresholds of very small, small, medium, large, and very large effects, respectively.	In contrast to the conventional rules of thumb provided by Cohen (1988), which have frequently been characterized as overly stringent in the context of psychological research, these adapted guidelines provide a more appropriate framework, as they were explicitly developed to reflect practical and theoretical significance of psychological effects (Funder & Ozer, 2019).
Additional influence diagnostics were conducted to investigate outliers.	These analyses were done to cross-validate leverage points identified in a leave-one-out analysis using the diagnostic procedures proposed by Viechtbauer and Cheung (2010).
An exploratory robustness check using Mahalonobis distance was conducted to identify the 20% most influential cases regarding the effect of participant age on sex differences in WLT performance.	Given the low median age in the data, due to the lack of older samples, this analysis was conducted to see whether the observed moderation effect of mean age was caused by outliers.
An exploratory cumulative meta-analysis according to publication year was conducted.	This additional analysis was conducted to further investigate the cross-temporal effect decline found in moderation analysis.
An additional meta-regression including the interaction of publication year and mean age as well as separate meta-regressions of effect sizes on publication year for each age group were computed.	This additional analysis was conducted to further investigate the cross-temporal effect decline found in moderation analysis.

Table S1. (*Continued.*)

Deviation	Rationale
For the multiverse and specification curve meta-analyses, the following *which* factors were recoded into less fine-grained categories: response format (draw WL vs. other vs. either), sex of first author (male vs. female vs. either), shape of vessel (rectangular vs. other vs. either), mode of presentation (drawing vs. other vs. either), sample type (undergraduates vs. other vs. either), age group (children vs. adolescents vs. adults vs. either).	This decision was made because many of the originally specified categories were represented by only a small number of samples, resulting in a large number of specifications based on comparably effect sizes. The adopted categories therefore yield more theoretically reasonable specifications, consistent with the principles for multiverse and specification curve meta-analysis outlined by Voracek et al. (2019).

References Appendix B

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Appendix C

PRISMA Checklist

Table S2. *PRISMA Checklist.*

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Cover Page
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	2
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	3
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	16
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	19
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	17
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	17
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	17
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	17
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	19, 20
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	19, 20
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	19
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	20
Synthesis	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention	20

Section and Topic	Item #	Checklist item	Location where item is reported
methods		characteristics and comparing against the planned groups for each synthesis (item #5)).	
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	20
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	21
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	21, 23
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	21, 22
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	21
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	22
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	22-24
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	18
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	17
Study characteristics	17	Cite each included study and present its characteristics.	27-48
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	58-61
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	27-48
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	59-61
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	26
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	52-57, 62-65
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	28
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	58-61
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	62-65

Section and Topic	Item #	Checklist item	Location where item is reported
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	66-69
	23b	Discuss any limitations of the evidence included in the review.	71,72
	23c	Discuss any limitations of the review processes used.	71,72
	23d	Discuss implications of the results for practice, policy, and future research.	69-72
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	17
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	17
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	17
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	–
Competing interests	26	Declare any competing interests of review authors.	–
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	26, 27

Note. Table template taken from Page et al. (2021).

Reference

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Appendix D

References of Excluded Studies

No WLT Used

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Appendix E

Description of Methods Used to Detect Dissemination Bias

All dissemination bias detection analyses except for PET-PEESE were performed using the online application MetaShine (Siegel et al., 2021) using published studies only. The rationales of the ten methods presently applied are outlined below.

p*-Curve, *p*-Uniform, *p*-Uniform

Three bias detection methods based on the *p*-value distributions of published effects were used to investigate potential effects of both publication bias and *p*-hacking (Siegel et al., 2022). *p*-curve (Simonsohn et al., 2014), *p*-uniform (van Assen et al., 2015), and *p*-uniform* (van Aert & van Assen, 2018) are based on similar ideas but differ slightly in their implementation. All three methods allow for the calculation of an adjusted summary effect size estimate considering the given *p*-value distribution, with *p*-uniform and *p*-uniform* providing means to compute confidence intervals.

p-curve depicts the distribution of *p*-values of nominally significant (i.e., $p < .05$) effects within a set of studies. Under the assumption that all studies reaching statistical significance have the same probability of being published, these studies should not be affected by publication bias. The shape of the *p*-curve allows assumptions on the evidential value of the given meta-analytical dataset. While a right-skewed curve contains significantly more *p*-values numerically closer to .01 than .05, indicating that the meta-analytical summary effect differs significantly from zero (i.e., the presence of evidential value), a left-skewed curve represents an abundance of *p*-values numerically close to .05, indicating selective reporting or *p*-hacking and no true non-nil effect. Finally, a uniform distribution indicates the lack of evidential value (Simonsohn et al., 2014). To statistically test the right-skew of the *p*-curve, a binomial test comparing observed and expected proportions of *p*-values < .025 and an additional continuous test are used (Simonsohn et al., 2015). Additionally, the lack of statistical power (and thus of evidential value) can be tested using a 33% power test, which examines whether the observed *p*-curve is flatter than would be expected under an average power of 33% (Simonsohn et al., 2014, 2015). According to the thresholds provided by Siegel et al. (2022), publication bias is indicated if significance levels of the test of right-skewedness are $p > .05$ of the half p-curve (i.e., all *p*-values < .025) or $p > .10$ for the full *p*-curve (i.e., all *p*-values < .05).

Similarly, *p*-uniform analyzes the distribution of statistically significant *p*-values and formally tests the skew of this distribution. In contrast to *p*-curve, this approach transforms *p*-values in a given dataset conditional on a fixed-effect and compares their distribution to uniformity (van Assen et al., 2015). A deviation at $p < .10$ is interpreted as indicative of publication bias (Siegel et al., 2022).

In response to criticisms of *p*-curve and *p*-uniform (e.g., the assumption of between-studies homogeneity and the use of only nominally significant findings), *p*-uniform* was developed. This approach includes both significant and non-significant effects and accounts for between-studies heterogeneity. *P*-uniform* allows for more accurate adjusted effect size estimates as larger numbers of effect sizes can be included and between-studies variance is considered (van Aert & van Assen, 2018). However, it should be noted that its performance deteriorates under extreme publication bias when only significant studies are included in a meta-analysis, particularly in the absence of heterogeneity (van Aert & Niemeyer, 2022). Moreover, bias detection methods based on *p*-values are generally considered to overestimate the evidential value of meta-analytical summary effects (Cooper et al., 2019).

Approaches Based on Funnel Plot Asymmetry

The funnel plot (Light & Pillemer, 1984) displays the association between sample size and effect magnitude, with larger studies appearing at the top and smaller studies at the bottom of the graph. In the absence of bias, studies should scatter symmetrically around the observed meta-analytical summary effect. An asymmetrical effect size distribution in reference to the summary effect indicates publication bias, with larger effect magnitudes at the bottom of the plot indicating small study effects (Borenstein et al., 2021). In the power-enhanced funnel plot (Kossmeier et al., 2020), statistical power of primary studies is visualized using a color scheme with colder colors representing higher study precision and warmer colors indicating lower power. Additionally, the plot depicts the results of the test of excess significance (detailed further below).

To address the shortcomings of visual inspection of the funnel plot, several statistical tests of funnel plot asymmetry have been introduced. First, in Sterne and Egger's regression model (Sterne & Egger, 2005), the standard normal deviate effect size is regressed on the inverse of the standard error (i.e., study precision). A significant intercept with a two-sided *p*-value < .10 indicates funnel plot asymmetry (i.e., small study effects) (Siegel et al., 2022).

Second, the rank correlation method introduced by Begg and Mazumdar (1994) computes an adjusted Kendall's rank correlation coefficient (Kendall's τ) between primary study effect sizes and their variances. A significant association ($p < .10$) is interpreted as indicative of publication bias (Siegel et al., 2022).

Third, the PET-PEESE method (Stanley & Doucouliagos, 2014) is regarded as an extension of Sterne and Egger's regression, using an adjusted effect size estimate in the absence of small study effects (Siegel et al., 2022). The *precision estimate test* (PET) involves a precision-weighted regression of the effect size on the standard error. Here, a significant slope indicates small study effects, and a significant intercept indicates a true non-zero effect. As this estimate appears to be biased when reaching statistical significance, an additional *precision-effect estimate with standard error* (PEESE), which uses the squared standard error as a predictor, is computed and interpreted as the adjusted summary effect (Stanley & Doucouliagos, 2014). If the adjusted estimate exceeds 20% the observed meta-analytical summary effect in either direction, the presence publication bias is assumed (Siegel et al., 2022).

Fourth, the trim-and-fill method (Duval & Tweedie, 2000) estimates the number of missing studies needed to establish full plot symmetry. In a non-parametric and iterative procedure, extreme cases are removed until the plot becomes symmetrical. The trimmed studies as well as their missing counterparts on the asymmetrical side are then filled back in, followed by a re-estimation of the meta-analytical summary effect with this adjusted study set. Bias is indicated if the adjusted estimate exceeds 20% of the observed effect size in either direction (Siegel et al., 2022).

Of note, methods aimed at investigating funnel plot asymmetry tend to lack statistical power and do not allow for the identification of the specific driver of small study effects (e.g., publication bias, true effect heterogeneity or chance) (Kossmeier et al., 2020).

Test of Excess Significance

The test of excess significance (Ioannidis & Trikalinos, 2007) calculates the average post-hoc statistical power of the included primary studies to detect the observed summary effect. The expected number of nominally significant studies based on these power calculations is then contrasted with the observed number of significant findings using a chi-squared test. If the resulting p-value is $< .10$, publication bias is assumed. However, several shortcomings of this test have been identified, including vulnerability to heterogeneity and to outliers (Siegel et al., 2022).

Selection Model Approach

The selection model approach introduced by Vevea and Woods (2005) assigns weights to primary study effects based on the associated *p*-values. The distribution of weights follows four a-priori defined scenarios, namely moderate one-tailed, severe one-tailed, moderate two-tailed, and severe two-tailed selections. For each scenario, adjusted and unadjusted estimates are compared. The presence of publication bias is inferred if the adjusted estimate exceeds 20% of the observed meta-analytical summary effect in either direction (Siegel et al., 2022).

References Appendix E

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Appendix F

R Code

```
################################################################################
# Code for "Sex differences in Piaget's Water Level Tasks: A Multiverse Meta-Analysis" #
# Code last edited: 11.01.2026 by Florence Dejardin                            #
################################################################################

# Libraries required
library(readxl)
library(haven)
library(metafor)
library(DT)
library(writexl)
library(ggplot2)
library(countrycode)
library(psych)
library(patchwork)
library(gridExtra)
library(ggpubr)
library(plyr)
library(ggpubr)
library(grid)

########################
#                      #
# Standard Meta-Analysis #
#                      #
######################

#########################################
# file required: MetaAnalysis_dataset_WLT.xlsx #
########################################

# Load data
##### replace source path
x <-
read_xlsx("/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/MetaAnalysis_datase
t_WLT.xlsx", sheet = 1)
datatable(x)

### Inspect descriptives

## total sample size
```

```
total_sample <- sum(x$sample_n)
print(total_sample)
range(x$sample_n)

## birthyear and age
x$birthyear <- as.numeric(x$birthyear)
summary(x$birthyear)
summary(x$age_mean)
sd(x$age_mean, na.rm = TRUE)

## age per age group
children <- subset(x, age_group == "children")
summary(children$age_mean)
sd(children$age_mean, na.rm = TRUE)

adolescents <- subset(x, age_group == "adolescents")
summary(adolescents$age_mean)
sd(adolescents$age_mean, na.rm = TRUE)

adults <- subset(x, age_group == "adults")
summary(adults$age_mean)
sd(adults$age_mean, na.rm = TRUE)

# group sizes
for (group in c("children", "adolescents", "adults")) {
  print(sum(x$age_group == group, na.rm = TRUE))
}

## sample type
for (sample in c("undergraduate students", "pupils", "general population", "healthy control
group")) {
  print(sum(x$sample_type == sample, na.rm = TRUE))
}

### Histogram for effects per study year (Pietschnig & Voracek, 2011 vs. Dejardin, 2025)

tiff("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/histogram_pubyear_final.tiff",
     width = 1000,
     height = 1000,
     pointsize = 17*2)

# create the histogram with transparent bars initially
hist_res <- hist(x$pub_year,
                 xlab = "Publication year",
                 ylab = "Sample count",
```

```
        main = "",
        breaks = 45,
        las = 2,
        xlim = c(1960, 2025),
        ylim = c(0, 20),
        lab = c(50, 50, 7),
        col = rgb(0, 0, 0, 0),
        border = NA,
        xaxt = "n")

# ydd x-axis with custom labels
axis(1, at = seq(1960, 2025, by = 5), las = 2)  # Rotate x-axis labels by 90 degrees, set steps to
5 years

# Find the breaks corresponding to 2009 to 2024
breaks <- hist_res$breaks
mids <- hist_res$mids
counts <- hist_res$counts

# identify the indices of the breaks corresponding to 2009 to 2025
year_start_index <- which.min(abs(mids - 2009))
year_end_index <- which.min(abs(mids - 2025))

# for years before 2009, create stacked bars based on new_Dejardin
for (i in seq_along(mids)) {
  if (i < year_start_index) {
    # Find studies in this year bin
    year_bin_start <- breaks[i]
    year_bin_end <- breaks[i + 1]

    # get studies in this bin
    studies_in_bin <- x[x$pub_year >= year_bin_start & x$pub_year < year_bin_end, ]

    # count studies by new_Dejardin
    count_dejardin_0 <- sum(studies_in_bin$new_Dejardin == 0, na.rm = TRUE)
    count_dejardin_1 <- sum(studies_in_bin$new_Dejardin == 1, na.rm = TRUE)

    # draw blue bar (new_Dejardin = 0) from bottom
    if (count_dejardin_0 > 0) {
      rect(year_bin_start, 0, year_bin_end, count_dejardin_0, col = "#0063A6")
    }

    # draw orange bar (new_Dejardin = 1) on top
    if (count_dejardin_1 > 0) {
```

```
    rect(year_bin_start, count_dejardin_0, year_bin_end, count_dejardin_0 +
count_dejardin_1, col = "#DD4814")
    }
  }
  # for years after 2024, keep original behavior but with new color
  else if (i > year_end_index) {
    rect(breaks[i], 0, breaks[i + 1], counts[i], col = "#0063A6")
  }
}

# draw the orange bars for the years 2009 to 2025
for (i in year_start_index:year_end_index) {
rect(breaks[i], 0, breaks[i + 1], counts[i], col = "#DD4814")
}

# add legend
legend("topright",
       legend = c("Dejardin et al. (2025)", "Pietschnig & Voracek (2011)"),
       fill = c("#DD4814", "#0063A6"),
       border = "black",
       bty = "n") # Remove legend box border

dev.off()

### plot sample origin world map
#### using adapted code from Oberleiter et al. (2023)

tiff("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/sample_origin_final.tiff",
width = 1800, height = 1000, pointsize = 20)
# prepare data
countries_raw <- x$sample_origin
countries_clean <- countries_raw
countries_clean[countries_clean %in% c("NA", "")] <- NA
countries_clean <- gsub("USA and Canada", "USA;Canada", countries_clean)
countries_clean <- gsub("Ghana and Norway", "Ghana;Norway", countries_clean)
countries_clean <- unlist(strsplit(countries_clean, ";"))
countries_clean <- gsub("England", "UK", countries_clean)
countries_clean <- trimws(countries_clean)
countries_clean <- countries_clean[!is.na(countries_clean) & countries_clean != ""]

# put data into data frame
countries_df <- data.frame(country = countries_clean, stringsAsFactors = FALSE)

# add country codes
countries <- countries_df$country
```

```
countries_df$country_code <- countrycode(countries, "country.name", "iso3c")
countries_df$country_code <- countrycode(countries_df$country_code, "iso3c",
"country.name")

# count effects per country
n_by_country <- table(countries_df$country_code)

# create final data frame
countries_final <- data.frame(
  country_code = names(n_by_country),
  n_by_country = as.numeric(n_by_country),
  stringsAsFactors = FALSE
)

# change labels for USA and UK
countries_final$country_code[countries_final$country_code == "United States"] <- "USA"
countries_final$country_code[countries_final$country_code == "United Kingdom"] <- "UK"

# create world map
world_map <- map_data("world")
world_map <- subset(world_map, region != "Antarctica")

# check if any more renaming is needed
setdiff(countries_final$country_code, unique(world_map$region))

# plot
world_wlt <-
  ggplot(countries_final) +
  geom_map(
    data = world_map, map = world_map, aes(map_id = region),
    fill = "grey90", color = "#7f7f7f", size = 0.25
  ) +
  geom_map(
    map = world_map,
    aes(fill = n_by_country, map_id = country_code),
    size = 0.2
  ) +
  scale_fill_gradientn(
    colours = c("navy", "blue", "cyan", "yellow", "orange", "red"),
    name = "Number of effects",
    na.value = "grey90",
    trans = "sqrt", # transform because data is highly scewed (most studies come from the US)
    breaks = c(1, 10, 25, 50, 80, 125)
  ) +
  expand_limits(x = world_map$long, y = world_map$lat) +
```

```
  theme_void() +
  theme(
    legend.title = element_text(size = 20),
    legend.text  = element_text(size = 16)
  )

world_wlt
dev.off()
```

Main analysis

```
# Cohen's d
summary(rma(x$d,x$d_Var,method="REML"))

# Hedge's g
summary(rma(x$g,x$g_Var,method="REML"))
```

Forest plot

```
# get Times New Roman font
quartzFonts(Times = quartzFont(c("Times New Roman",
                                 "Times New Roman",
                                 "Times New Roman",
                                 "Times New Roman")))

# split indices (to fit six subplots onto three pages)
k  <- res$k
k1 <- ceiling(k / 6)
k2 <- ceiling(2 * k / 6)
k3 <- ceiling(3 * k / 6)
k4 <- ceiling(4 * k / 6)
k5 <- ceiling(5 * k / 6)

# indices for six subsets
idx1 <- 1:k1
idx2 <- (k1 + 1):k2
idx3 <- (k2 + 1):k3
idx4 <- (k3 + 1):k4
idx5 <- (k4 + 1):k5
idx6 <- (k5 + 1):k

# subset data
x_1 <- x[idx1, ]
x_2 <- x[idx2, ]
```

```
x_3 <- x[idx3, ]
x_4 <- x[idx4, ]
x_5 <- x[idx5, ]
x_6 <- x[idx6, ]

# perform overall analysis
res_all <- rma(x$d, x$d_Var, method = "REML", slab = x$AU)

# page 1
tiff("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/forestplot_thesis_page1.tiff",
    width  = 17000,
    height = 11000,
    pointsize = 20,
    res    = 600,
    compression = "lzw+p",
    family = "Times")
par(family = "Times")
par(mfrow = c(1,2))

# subplot 1
res_1 <- rma(x_1$d, x_1$d_Var, method = "REML")
k_1   <- res_1$k

forest(res_1,
       slab     = x_1$AU,
       annotate = TRUE,
       header   = c("Author(s) and publication year",
                    "Cohen's d [95% CI]"),
       addcred  = TRUE,
       addfit   = FALSE,
       col      = "red",
       xlab     = "Standardized mean difference",
       steps    = 5,
       mlab     = "",
       xlim     = c(-4.5, 4),
       alim     = c(-2, 2),
       lwd      = 1.3,
       top      = 1,
       ylim     = c(0, k_1 + 1))

# subplot 2
res_2 <- rma(x_2$d, x_2$d_Var, method = "REML")
k_2   <- res_2$k

forest(res_2,
```

```
       slab     = x_2$AU,
       annotate = TRUE,
       header   = c("Author(s) and publication year",
                    "Cohen's d [95% CI]"),
       addcred  = TRUE,
       addfit   = FALSE,
       col      = "red",
       xlab     = "Standardized mean difference",
       steps    = 5,
       mlab     = "",
       xlim     = c(-4.5, 4),
       alim     = c(-2, 2),
       lwd      = 1.3,
       top      = 1,
       ylim     = c(0, k_2 + 1))

dev.off()

# page 2
tiff("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/forestplot_thesis_page2.tiff",
     width  = 17000,
     height = 11000,
     pointsize = 20,
     res    = 600,
     compression = "lzw+p",
     family = "Times")
par(family = "Times")
par(mfrow = c(1,2))

# subplot 3
res_3 <- rma(x_3$d, x_3$d_Var, method = "REML")
k_3   <- res_3$k

forest(res_3,
       slab     = x_3$AU,
       annotate = TRUE,
       header   = c("Author(s) and publication year",
                    "Cohen's d [95% CI]"),
       addcred  = TRUE,
       addfit   = FALSE,
       col      = "red",
       xlab     = "Standardized mean difference",
       steps    = 5,
       mlab     = "",
       xlim     = c(-4.5, 4),
```

```
       alim     = c(-2, 2),
       lwd      = 1.3,
       top      = 1,
       ylim     = c(0, k_3 + 1))

# subplot 4
res_4 <- rma(x_4$d, x_4$d_Var, method = "REML")
k_4   <- res_4$k

forest(res_4,
       slab     = x_4$AU,
       annotate = TRUE,
       header   = c("Author(s) and publication year",
                    "Cohen's d [95% CI]"),
       addcred  = TRUE,
       addfit   = FALSE,
       col      = "red",
       xlab     = "Standardized mean difference",
       steps    = 5,
       mlab     = "",
       xlim     = c(-4.5, 4),
       alim     = c(-2, 2),
       lwd      = 1.3,
       top      = 1,
       ylim     = c(0, k_4 + 1))

dev.off()

# page 3
tiff("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/forestplot_thesis_page3.tiff",
     width  = 17000,
     height = 11000,
     pointsize = 20,
     res    = 600,
     compression = "lzw+p",
     family = "Times")
par(family = "Times")
par(mfrow = c(1,2))

# subplot 5
res_5 <- rma(x_5$d, x_5$d_Var, method = "REML")
k_5   <- res_5$k

forest(res_5,
       slab     = x_5$AU,
```

```
      annotate = TRUE,
      header   = c("Author(s) and publication year",
                   "Cohen's d [95% CI]"),
      addcred  = TRUE,
      addfit   = FALSE,
      col      = "red",
      xlab     = "Standardized mean difference",
      steps    = 5,
      mlab     = "",
      xlim     = c(-4.5, 4),
      alim     = c(-2, 2),
      lwd      = 1.3,
      top      = 1,
      ylim     = c(0, k_5 + 1))

# subplot 6 (with overall summary)
res_6 <- rma(x_6$d, x_6$d_Var, method = "REML")
k_6   <- res_6$k

rows_6 <- forest(res_6,
             slab     = x_6$AU,
             annotate = TRUE,
             header   = c("Author(s) and publication year",
                          "Cohen's d [95% CI]"),
             addcred  = TRUE,
             addfit   = FALSE,
             col      = "red",
             xlab     = "Standardized mean difference",
             steps    = 5,
             mlab     = "",
             xlim     = c(-4.5, 4),
             alim     = c(-2, 2),
             lwd      = 1.3,
             top      = 1,
             ylim     = c(-2, k_6 + 1))

# place overall summary two lines below last study
last_row    <- min(rows_6$rows)
overall_row <- min(rows_6$rows) - 2
line_y      <- (last_row + overall_row) / 2

# draw black line
usr <- par("usr")
segments(x0 = usr[1],
         y0 = line_y,
```

```
        x1 = usr[2],
        y1 = line_y,
        lwd = 1.5)

# add overall summary effect
addpoly(res_all,
        row     = overall_row,
        mlab    = "",
        col     = "red",
        lcol    = "red",
        addcred = TRUE)

dev.off()


### Robustness checks

# perform RMA
res <- rma(x$d, x$d_Var, method = "REML")

## Leave-one-out analysis
loo_res <- leave1out(res)

# convert the results to a data frame
loo_table <- as.data.frame(loo_res)

# add author column
loo_table <- cbind(AU = x$AU, loo_table)

# create excel file
write.xlsx(loo_table, file =
"/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/WLT_LOO.xlsx")

## Influence diagnostics

# perform influence analysis
inf <- influence(res)

# check influencial cases
x[inf$is.infl, 2]

# plot influencial data
tiff("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/influence_analysis_final.tiff",
width = 15.5, height = 15.5, units = "cm", res = 600)
plot(inf)
```

```
dev.off()

# repeat analysis without leverage points
res_no_infl <- rma(x$d, x$d_Var, method = "REML", subset = !inf$is.infl)
summary(res_no_infl)


### Moderator analyses

### Subgroup analyses

## response format (leave out mixed and adjust WL as k = 1 and k = 0, respectively)

# perform separate meta-analyses
res1 <- rma(x$d, x$d_Var, data = x, subset=response=="MC")
res2 <- rma(x$d, x$d_Var, data = x, subset=response=="draw WL")
res3 <- rma(x$d, x$d_Var, data = x, subset=response=="adjust WL")
summary(res1)
summary(res2)
summary(res3)

# conduct moderator analysis
x_sub1 <- subset(x, response %in% c("MC", "draw WL", "adjust WL"))
res_mod1 <- rma(yi = d, vi = d_Var, mods = ~ factor(response), method = "REML", data =
x_sub1)
summary(res_mod1)


## group vs individual testing

# perform separate meta-analyses
res1 <- rma(x$d, x$d_Var, data = x, subset=testsit=="group")
res2 <- rma(x$d, x$d_Var, data = x, subset=testsit=="individual")
summary(res1)
summary(res2)

# conduct moderator analysis
x_sub2 <- subset(x, testsit %in% c("group", "individual"))
res_mod2 <- rma(yi = d, vi = d_Var, mods = ~ factor(testsit), method = "REML", data =
x_sub2)
summary(res_mod2)


## published vs unpublished studies
```

```
# perform separate meta-analyses
res1 <- rma(x$d, x$d_Var, data = x, subset=dummy_publ==1)
res2 <- rma(x$d, x$d_Var, data = x, subset=dummy_publ==0)
summary(res1)
summary(res2)

# conduct moderator analysis
res_mod3 <- rma(yi = d, vi = d_Var, mods = ~ factor(dummy_publ), method = "REML", data
= x)
summary(res_mod3)


## horizontal vs no horizontal reference line
res1 <- rma(x$d, x$d_Var, data = x, subset=horizontal=="yes")
res2 <- rma(x$d, x$d_Var, data = x, subset=horizontal=="no")
summary(res1)
summary(res2)

# conduct moderator analysis
x_sub4 <- subset(x, horizontal %in% c("yes", "no"))
res_mod4 <- rma(yi = d, vi = d_Var, mods = ~ factor(horizontal), method = "REML", data =
x_sub4)
summary(res_mod4)


## speed vs power test

# perform separate meta-analyses
res1 <- rma(x$d, x$d_Var, data = x, subset=speedpower=="power")
res2 <- rma(x$d, x$d_Var, data = x, subset=speedpower=="speed")
summary(res1)
summary(res2)

# conduct moderator analysis
x_sub5 <- subset(x, speedpower %in% c("power", "speed"))
res_mod5 <- rma(yi = d, vi = d_Var, mods = ~ factor(speedpower), method = "REML", data
= x_sub5)
summary(res_mod5)


## shape of vessel
freq_table1 <- table(x$vessel)
freq_table1

# perform separate meta-analyses
```

```
res1 <- rma(x$d, x$d_Var, data = x, subset=vessel=="rectangular")
res2 <- rma(x$d, x$d_Var, data = x, subset=vessel=="cylindrical")
res3 <- rma(x$d, x$d_Var, data = x, subset=vessel=="florence flask")
res4 <- rma(x$d, x$d_Var, data = x, subset=vessel=="mixed shapes")
res5 <- rma(x$d, x$d_Var, data = x, subset=vessel=="jar")
res6 <- rma(x$d, x$d_Var, data = x, subset=vessel=="glass/cup")
res7 <- rma(x$d, x$d_Var, data = x, subset=vessel=="bottle")
summary(res1)
summary(res2)
summary(res3)
summary(res4)
summary(res5)
summary(res6)
summary(res7)

# conduct moderator analysis
x_sub6 <- subset(x, vessel %in% c("rectangular", "curved / wine bottle", "florence flask",
"mixed shapes", "jar", "glass/cup", "bottle"))
res_mod6 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6)
summary(res_mod6)

# omnibus test is significant; repeat without 'mixed' category
x_sub6 <- subset(x, vessel %in% c("rectangular", "bottle", "florence flask", "jar", "glass/cup",
"cylindrical"))
res_mod6 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6)
summary(res_mod6)
# not significant anymore

## pairwise comparisons between mixed shapes category and other shapes

# mixed shapes vs. rectangular
x_sub6_1 <- subset(x, vessel %in% c("rectangular", "mixed shapes"))
res_mod6_1 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_1)
summary(res_mod6_1)

# mixed shapes vs. bottle
x_sub6_2 <- subset(x, vessel %in% c("bottle", "mixed shapes"))
res_mod6_2 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_2)
summary(res_mod6_2)

# mixed shapes vs. florence flask
```

```
x_sub6_3 <- subset(x, vessel %in% c("florence flask", "mixed shapes"))
res_mod6_3 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_3)
summary(res_mod6_3)

# mixed shapes vs. jar
x_sub6_4 <- subset(x, vessel %in% c("jar", "mixed shapes"))
res_mod6_4 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_4)
summary(res_mod6_4)

# mixed shapes vs. glass/cup
x_sub6_5 <- subset(x, vessel %in% c("glass/cup", "mixed shapes"))
res_mod6_5 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_5)
summary(res_mod6_5)

# mixed shapes vs. cylindrical
x_sub6_6 <- subset(x, vessel %in% c("cylindrical", "mixed shapes"))
res_mod6_6 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_6)
summary(res_mod6_6)

## pairwise comparisons between other shapes

# rectangular vs. bottle
x_sub6_7 <- subset(x, vessel %in% c("bottle", "rectangular"))
res_mod6_7 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_7)
summary(res_mod6_7)

# rectangular vs. florence flask
x_sub6_8 <- subset(x, vessel %in% c("florence flask", "rectangular"))
res_mod6_8 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_8)
summary(res_mod6_8)

# rectangular vs. jar
x_sub6_9 <- subset(x, vessel %in% c("jar", "rectangular"))
res_mod6_9 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_9)
summary(res_mod6_9)

# rectangular vs. glass/cup
x_sub6_10 <- subset(x, vessel %in% c("glass/cup", "rectangular"))
```

```
res_mod6_10 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_10)
summary(res_mod6_10)

# rectangular vs. cylindrical
x_sub6_11 <- subset(x, vessel %in% c("cylindrical", "rectangular"))
res_mod6_11 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_11)
summary(res_mod6_11)

# bottle vs. florence flask
x_sub6_12 <- subset(x, vessel %in% c("bottle", "florence flask"))
res_mod6_12 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_12)
summary(res_mod6_12)

# bottle vs. jar
x_sub6_13 <- subset(x, vessel %in% c("bottle", "jar"))
res_mod6_13 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_13)
summary(res_mod6_13)

# jar vs florence flask
x_sub6_14 <- subset(x, vessel %in% c("florence flask", "jar"))
res_mod6_14 <- rma(yi = d, vi = d_Var, mods = ~ factor(vessel), method = "REML", data =
x_sub6_14)
summary(res_mod6_14)


## sex of first author

# perform separate meta-analyses
res1 <- rma(x$d, x$d_Var, data = x, subset=AU_sex=="male")
res2 <- rma(x$d, x$d_Var, data = x, subset=AU_sex=="female")
summary(res1)
summary(res2)

# conduct moderator analysis
x_sub7 <- subset(x, AU_sex %in% c("male", "female"))
res_mod7 <- rma(yi = d, vi = d_Var, mods = ~ factor(AU_sex), method = "REML", data =
x_sub7)
summary(res_mod7)


## mode of presentation
```

```
freq_table2 <- table(x$vorgabe)
freq_table2

# perform separate meta-analyses
res1 <- rma(x$d, x$d_Var, data = x, subset=vorgabe=="drawing")
res2 <- rma(x$d, x$d_Var, data = x, subset=vorgabe=="real vessel")
res3 <- rma(x$d, x$d_Var, data = x, subset=vorgabe=="screen")
res4 <- rma(x$d, x$d_Var, data = x, subset=vorgabe=="photograph of vessel")
summary(res1)
summary(res2)
summary(res3)
summary(res4)

# conduct moderator analysis
x_sub8 <- subset(x, vorgabe %in% c("drawing", "real vessel", "screen", "photograph of
vessel"))
res_mod8 <- rma(yi = d, vi = d_Var, mods = ~ factor(vorgabe), method = "REML", data =
x_sub8)
summary(res_mod8)


## participant origin (continents)

freq_table3 <- table(x$origin_continent)
freq_table3

# perform separate meta-analyses
res1 <- rma(x$d, x$d_Var, data = x, subset=origin_continent=="North America")
res2 <- rma(x$d, x$d_Var, data = x, subset=origin_continent=="Europe")
res3 <- rma(x$d, x$d_Var, data = x, subset=origin_continent=="Asia")
res4 <- rma(x$d, x$d_Var, data = x, subset=origin_continent=="Africa")
res5 <- rma(x$d, x$d_Var, data = x, subset=origin_continent=="Australia")
summary(res1)
summary(res2)
summary(res3)
summary(res4)
summary(res5)

# conduct moderator analysis
x_sub9 <- subset(x, origin_continent %in% c("North America", "Europe", "Asia", "Africa",
"Australia"))
res_mod9 <- rma(yi = d, vi = d_Var, mods = ~ factor(origin_continent), method = "REML",
data = x_sub9)
summary(res_mod9)
```

```
# sample type
freq_table4 <- table(x$sample_type)
freq_table4

# perform separate meta-analyses
res1 <- rma(x$d, x$d_Var, data = x, subset=sample_type=="undergraduate students")
res2 <- rma(x$d, x$d_Var, data = x, subset=sample_type=="pupils")
res3 <- rma(x$d, x$d_Var, data = x, subset=sample_type=="general population")
res4 <- rma(x$d, x$d_Var, data = x, subset=sample_type=="healthy control group")
res5 <- rma(x$d, x$d_Var, data = x, subset=sample_type=="other")
summary(res1)
summary(res2)
summary(res3)
summary(res4)
summary(res5)

# conduct moderator analysis
x_sub10 <- subset(x, sample_type %in% c("undergraduate students", "pupils", "general
population", "healthy control group", "other"))
res_mod10 <- rma(yi = d, vi = d_Var, mods = ~ factor(origin_continent), method = "REML",
data = x_sub10)
summary(res_mod10)

# age group (leave out mixed as k = 1)

# perform separate meta-analyses
res1 <- rma(x$d, x$d_Var, data = x, subset=age_group=="children")
res2 <- rma(x$d, x$d_Var, data = x, subset=age_group=="adolescents")
res3 <- rma(x$d, x$d_Var, data = x, subset=age_group=="adults")
summary(res1)
summary(res2)
summary(res3)

# conduct moderator analysis
x_sub11 <- subset(x, age_group %in% c("children", "adolescents", "adults"))
res_mod11 <- rma(yi = d, vi = d_Var, mods = ~ factor(age_group), method = "REML", data =
x_sub11)
summary(res_mod11)

## omnibus test is significant; conduct pairwise comparisons

# children vs adolescents
x_sub11_1 <- subset(x, age_group %in% c("children", "adolescents"))
```

```
res_mod11_1 <- rma(yi = d, vi = d_Var, mods = ~ factor(age_group), method = "REML",
data = x_sub8_1)
summary(res_mod11_1)

# children vs adults
x_sub11_2 <- subset(x, age_group %in% c("children", "adults"))
res_mod11_2 <- rma(yi = d, vi = d_Var, mods = ~ factor(age_group), method = "REML",
data = x_sub8_2)
summary(res_mod11_2)

# adolescents vs adults
x_sub11_3 <- subset(x, age_group %in% c("adolescents", "adults"))
res_mod11_3 <- rma(yi = d, vi = d_Var, mods = ~ factor(age_group), method = "REML",
data = x_sub8_3)
summary(res_mod11_3)


## exploratory analysis: result mode

freq_table5 <- table(x$res_mode)
freq_table5

# group res_mode variable according to categorical and metric outcomes
x$res_mode_grp <- NA
# categorical outcomes
x$res_mode_grp[x$res_mode %in% c("# failed Ss", "# successful Ss", "% successful Ss")] <-
"res_categorical"
# metric outcomes (correct items)
x$res_mode_grp[x$res_mode %in% c("mean # correct items", "mean # erroneous items", "%
correct items")] <- "res_metric_items"
# metric outcomes (degrees of deviation)
x$res_mode_grp[x$res_mode %in% c("mean deviation (°) off horizontal")] <-
"res_metric_degrees"

# conduct separate meta-analyses

res1 <- rma(x$d, x$d_Var, data = x, subset=res_mode_grp=="res_categorical")
res2 <- rma(x$d, x$d_Var, data = x, subset=res_mode_grp=="res_metric_items")
res3 <- rma(x$d, x$d_Var, data = x, subset=res_mode_grp=="res_metric_degrees")
summary(res1)
summary(res2)
summary(res3)

# conduct moderator analysis
x_sub12 <- subset(x, !is.na(res_mode_grp))
```

```
res_mod12 <- rma(yi = d, vi = d_Var, mods = ~ factor(res_mode_grp), method = "REML",
data = x_sub9)
summary(res_mod12)


### Precision-weighted meta-regressions

## mean age
res_age <- rma(x$d, x$d_Var, mods = ~ age_mean, data = x)
summary(res_age)

# regression plot for age
tiff("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/metareg_age_final.tiff",width=
1200,height=1200,pointsize=17*2)
plot(x$age_mean, x$d,
    xlab = "Mean age",
    ylab = "Standardized mean difference",
    main = "",
    pch = 21,   # Use pch = 21 for outlined circles
    #alpha.f = 0.75,
    #col = "darkblue",  # Border color of the points
    col = adjustcolor("#666666", alpha.f = 0.75),
    bg = NA,  # Fill color of the points
    cex = sqrt(x$sample_n) / max(sqrt(x$sample_n)) * 5,  # Adjust point size
    xlim = c(0, 80),  # Set x-axis limits
    lwd = 2.5,
    xaxt = "n")  # Turn off x-axis labels initially

# Add the fitted meta-regression line
pred <- predict(res_age, newmods = seq(0, 80, length.out = 100))
lines(seq(0, 80, length.out = 100), pred$pred, col = "#DD4814", lwd = 7)

# Optionally, add confidence interval lines
lines(seq(0, 80, length.out = 100), pred$ci.lb, col = "#DD4814", lwd = 4, lty = 3)
lines(seq(0, 80, length.out = 100), pred$ci.ub, col = "#DD4814", lwd = 4, lty = 3)

# Add x-axis with custom labels
axis(1, at = seq(0, 80, by = 5), las = 2)  # Rotate x-axis labels by 90 degrees, set steps to 5
years
dev.off()

# exploratory robustness check using Mahalonobis distance
md_age <- mahalanobis(x[, c("age_mean", "d")],
                colMeans(x[, c("age_mean", "d")], na.rm = TRUE),
                cov(x[, c("age_mean", "d")], use = "complete.obs"))
```

```
x$outlier_mahalanobis_age <- md_age > qchisq(0.80, df = 2)
x80_mahalanobis_age <- subset(x, !outlier_mahalanobis_age & is.finite(d) & is.finite(d_Var)
& is.finite(age_mean))

cutoff_mahalanobis_age <- quantile(md_age, 0.80, na.rm = TRUE)         # 80th percentile
is_infl_mahalanobis_age <- md_age > cutoff_mahalanobis_age

# re-fit model with only the 80% most typical values (in terms of Mahalonibis distance)
res80_mahalanobis_age <- rma(x80_mahalanobis_age$d, x80_mahalanobis_age$d_Var,
mods = ~ age_mean, data = x80_mahalanobis_age)
summary(res80_mahalanobis_age)

# plot result

# format points
pt_cex <- sqrt(x$sample_n) / max(sqrt(x$sample_n), na.rm = TRUE) * 5
pt_col <- ifelse(is_infl_mahalanobis_age,
              adjustcolor("#94C154", alpha.f = 0.90),  # influential (top 20%)
              adjustcolor("#666666", alpha.f = 0.75))  # typical (80%)

# predictions from fitted model
yrs_age <- seq(0, 80, length.out = 100)
pred_full_age <- predict(res_age, newmods = yrs_age)
pred_core_mahalanobis_age <- predict(res80_mahalanobis_age, newmods = yrs_age)

# create plot
tiff("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/metareg_age_mahalanobis_fin
al.tiff",
    width = 1200, height = 1200, pointsize = 17*2)

plot(x$age_mean, x$d,
    xlab = "Mean age",
    ylab = "Standardized mean difference",
    main = "",
    pch = 21,                          # outlined circles
    col = pt_col,                      # border color varies by influence
    bg = NA,                           # hollow
    cex = pt_cex,                      # bubble size
    xlim = c(0, 80),
    lwd = 2.5,
    xaxt = "n")                        # custom axis next

# regression lines

# full model line
```

```
lines(yrs_age, pred_full_age$pred, col = "black", lwd = 5)

# Core-80% model line (Mahalonibis distance)
lines(yrs_age, pred_core_mahalanobis_age$pred,  col = "#DD4814", lwd = 7)
lines(yrs_age, pred_core_mahalanobis_age$ci.lb, col = "#DD4814", lwd = 4, lty = 3)
lines(yrs_age, pred_core_mahalanobis_age$ci.ub, col = "#DD4814", lwd = 4, lty = 3)

# x-axis with 5-year ticks, vertical labels
axis(1, at = seq(0, 80, by = 5), las = 2)

# legend
legend("topright",
       legend = c("Full model (all studies)",
                  "Core model (80% least influential)",
                  "Top 20% most influential"),
       pt.bg = NA, pch = c(NA, NA, 21), pt.cex = c(NA, NA, 1.4),
       col = c("black", "#DD4814", adjustcolor("#94C154", 0.90)),
       lwd = c(5, 7, 2.5), lty = c(1, 1, NA), #cex = 0.7,
       bty = "o", box.col = "black",)

dev.off()


## birth year
res_birthyear <- rma(x$d, x$d_Var, mods = ~ birthyear, data = x)
summary(res_birthyear)


## publication year
res_pubyear <- rma(x$d, x$d_Var, mods = ~ pub_year, data = x)
summary(res_pubyear)

# regression plot for publication year
tiff("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/metareg_pubyear_final.tiff",wi
dth=1200,height=1200,pointsize=17*2)
plot(x$pub_year, x$d,
     xlab = "Publication year",
     ylab = "Standardized mean difference",
     main = "",
     pch = 21,
     col = adjustcolor("#0063A6", alpha.f = 0.75),
     bg = NA,
     cex = sqrt(x$sample_n) / max(sqrt(x$sample_n)) * 5,
     xlim = c(1960, 2025),
     lwd = 2.5,
```

```
    xaxt = "n")

# add fitted meta-regression line
pred <- predict(res_pubyear, newmods = seq(1960, 2025, length.out = 100))
lines(seq(1960, 2025, length.out = 100), pred$pred, col = "#DD4814", lwd = 7)

# add confidence interval lines
lines(seq(1960, 2025, length.out = 100), pred$ci.lb, col = "#DD4814", lwd = 4, lty = 3)
lines(seq(1960, 2025, length.out = 100), pred$ci.ub, col = "#DD4814", lwd = 4, lty = 3)

# add x-axis with custom labels
axis(1, at = seq(1960, 2025, by = 5), las = 2)
dev.off()


## exploratory analysis of interaction of publication year and age

# perform meta-regression with interaction
res_pubyear_age <- rma(x$d, x$d_Var, mods = ~ pub_year * age_mean, data = x)
summary(res_pubyear_age)

## separate meta-regressions for age groups

# children
res.children <- rma(children$d, children$d_Var, mods = ~ pub_year, data = children)
res.children

#adolescents
res.adolescents <- rma(adolescents$d, adolescents$d_Var, mods = ~ pub_year, data =
adolescents)
res.adolescents

# adults
res.adults <- rma(adults$d, adults$d_Var, mods = ~ pub_year, data = adults)
res.adults

## follow-up interaction models

# reference: adolescents
x_age_sub <- subset(x, age_group %in% c("children", "adolescents", "adults"))
res_age_pubyear1 <- rma(yi = d, vi = d_Var, mods = ~ pub_year * factor(age_group), method
= "REML", data = x_age_sub)
summary(res_age_pubyear1)

# reference: children
```

```
x_age_sub$age_group <- factor(x_age_sub$age_group, levels = c("children", "adolescents",
"adults"))
res_age_pubyear2 <- rma(yi = d, vi = d_Var, mods = ~ pub_year * factor(age_group), method
= "REML", data = x_age_sub)
summary(res_age_pubyear2)

# reference: adults
x_age_sub$age_group <- factor(x_age_sub$age_group, levels = c("adults", "adolescents",
"children"))
res_age_pubyear3 <- rma(yi = d, vi = d_Var, mods = ~ pub_year * factor(age_group), method
= "REML", data = x_age_sub)
summary(res_age_pubyear3)

## plot interaction of publication year and age

# define colors
age_colors <- c("children" = "#94C154", "adolescents" = "#DD4814", "adults" = "#11897A")

# create plot
tiff("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/pubyear_age_final.tiff",
width=1200,height=1200,pointsize=17*2)

# filter data to include only specified age groups in the legend
legend_labels <- c("children", "adolescents", "adults")
x_subset <- x[x$age_group %in% legend_labels, ]

# scatter plot of effect sizes vs. pub_year, weighted by sample size (inverse variance)
plot(x_subset$pub_year, x_subset$d, pch = 21, col =
adjustcolor(age_colors[x_subset$age_group], alpha.f = 0.75),
    cex = sqrt(x_subset$sample_n / max(x_subset$sample_n)) * 5,  # adjust size based on
sample_n
    xlab = "Publication year", ylab = "Standardized mean difference", xlim = c(1960, 2025),
lwd = 3, xaxt = "n")

# create regression lines for each age group

#children
pred.children <- predict(res.children, newmods = seq(1960, 2025, length.out = 100))
lines(seq(1960, 2025, length.out = 100), pred.children$pred, col = "#94C154", lwd = 7)

# adolescents
pred.adolescents <- predict(res.adolescents, newmods = seq(1960, 2025, length.out = 100))
lines(seq(1960, 2025, length.out = 100), pred.adolescents$pred, col = "#DD4814", lwd = 7)

# adults
```

```
pred.adults <- predict(res.adults, newmods = seq(1960, 2025, length.out = 100))
lines(seq(1960, 2025, length.out = 100), pred.adults$pred, col = "#11897A", lwd = 7)

# add legend
legend("topright", legend = legend_labels, col = age_colors[legend_labels], pch = 21, lwd =
1.8)

# add axis
axis(1, at = seq(1960, 2025, by = 5), las = 2)

dev.off()


## number of items
res_items <- rma(yi = x$d, vi = x$d_Var, mods = ~ items, data = x)
summary(res_items)
```

Publication bias

```
## all publication bias methods except pet-peese will be performed with Meta-Shine
(https://the-meta-analysis-project.shinyapps.io/MetaShine/)

# create dataset using the format required by Meta-Shine

# add SE-column to full data
x$d_SE <- sqrt(x$d_Var)

# create bias dataset
bias_data <- data.frame(
  studyname = x$AU,
  n       = x$sample_n,
  d       = x$d,
  d.SE     = x$d_SE,
  pub      = x$dummy_publ,
  year     = x$pub_year
)

# only work with published studies
bias_data_pub <- subset(bias_data, pub == 1)

# save as sav-file
write_sav(bias_data_pub,
"/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/bias_data_final_pub.sav")
```

```
## PET-PEESE

# prepare data
bias_data_pub$d.SE2 <- bias_data_pub$d.SE^2
bias_data_pub$weights <- 1 / bias_data_pub$d.SE^2

# PET
res_pet <- rma(yi = d, vi = d.SE2, method = "ML", mods = ~d.SE, data = bias_data_pub)
summary(res_pet)
# if intercept is significant at p < .10, PEESE estimate is interpreted as adjusted effect size

# PEESE
res_peese <- rma(yi = d, vi = d.SE2, method = "ML", mods = ~d.SE2, data = bias_data_pub)
summary(res_peese)

# get unadjusted estimate
res_unadj <- rma(x$d,x$d_Var,method="REML")
d_unadj <- res_unadj$b[1]
# get adjusted estimate
d_adj_peese <- res_peese$b[1]
# get percent difference
percent_diff <- (d_unadj - d_adj_peese) / d_unadj * 100
percent_diff

#########################
#                       #
# Multiverse Meta-Analyses #
#                       #
#########################

#######################################
# file needed: Multiverse_dataset_WLT.xlsx #
#######################################

################## code adapted from Voracek et al. (2019) #################
##################### available at https://osf.io/nkv46 #####################
```

Multiverse and specification curve meta-analysis

```
### prepare specifications dataset

# load meta-analytic data
##### replace source path
```

```
multiverse_data <-
read_excel('/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/Multiverse_dataset_f
inal.xlsx')
##### edit: for compatability with bootstrap analysis, only keep rows with d and g
multiverse_data <- multiverse_data[!is.na(multiverse_data$g) &
!is.na(multiverse_data$g_Var), ]
###### edit: add consecutive row ID
multiverse_data$id <- 1:nrow(multiverse_data)

# Construct grouping factors (internal, which factors)
author_sex <- c("male", "female", "total_sex")
age_group <- c("children", "adolescents", "adults", "total_age")
#sample_type <- c("pupils/students", "other_sample", "total_sample")
sample_type <- c("undergraduate students", "other_sample", "total_sample") # changed this
because it makes more sense to isolate undergraduates
origin <- c("North America", "other_origin", "total_origin") # "Greece", "Australia", "Italy",
"Oman", "Norway", "Netherlands", "Austria", "Singapore", "Switzerland", "Sweden", "India",
"either")
response <- c("draw WL", "other_response", "total_response")
published <- c("published", "unpublished", "total_published")
test_sit <- c("individual", "group", "total_testsit")
horizontal_ref <- c("yes", "no", "total_ref")
vessel_shape <- c("rectangular", "other_shape", "total_shape")

# different methods (external, how factors)
effect <- c("d", "g")
# ma_method <- c("FE", "RE_DL", "REML", "unweighted")
ma_method <- c("FE", "REML")

# Construct all possible combinations of internal and external factors
specifications <- expand.grid(author_sex = author_sex, age_group = age_group, sample_type
= sample_type, origin = origin, response = response, published = published, test_sit = test_sit,
horizontal_ref = horizontal_ref, vessel_shape = vessel_shape, effect = effect, ma_method =
ma_method)
specifications <- data.frame(ID = 1:nrow(specifications), specifications, mean = rep(NA,
nrow(specifications)), lb = rep(NA, nrow(specifications)), ub = rep(NA,
nrow(specifications)), p = rep(NA, nrow(specifications)), k = rep(NA, nrow(specifications)))
#### edit: add an ID column for bootstrap analysis

# Conduct specification analyses
for(i in 1:nrow(specifications)) {
  dat <- xmultiverse_data

  cat("Specification", i, "of", nrow(specifications), "...\n")
```

```
#############################################################
#### Determine specification subset by using "Which" factors #######
############################################################
# author_sex
if(specifications$author_sex[i] == "male") {
  dat <- dat[dat$AU_sex == "male", ]
} else if(specifications$author_sex[i] == "female") {
  dat <- dat[dat$AU_sex == "female", ]
}

# age_group
if(specifications$age_group[i] == "children") {
  dat <- dat[dat$age_group == "children", ]
} else if(specifications$age_group[i] == "adolescents") {
  dat <- dat[dat$age_group == "adolescents", ]
} else if(specifications$age_group[i] == "adults") {
  dat <- dat[dat$age_group == "adults", ]
}

# sample_type
if(specifications$sample_type[i] == "undergraduate students") {
  dat <- dat[dat$sample_type == "undergraduate students", ]
} else if(specifications$sample_type[i] == "other_sample") {
  dat <- dat[dat$sample_type == "other", ]
}

# origin
if(specifications$origin[i] == "North America") {
  dat <- dat[dat$sample_origin == "North America", ]
} else if(specifications$origin[i] == "other_origin") {
  dat <- dat[dat$sample_origin == "other", ]
}

# response
if(specifications$response[i] == "draw WL") {
  dat <- dat[dat$response == "draw WL", ]
} else if(specifications$response[i] == "other_response") {
  dat <- dat[dat$response == "other", ]
}

# publication status
if(specifications$published[i] == "published") {
  dat <- dat[dat$published == "yes", ]
} else if(specifications$published[i] == "unpublished") {
  dat <- dat[dat$published == "no", ]
```

```
}

# test_sit
if(specifications$test_sit[i] == "individual") {
  dat <- dat[dat$testsit == "individual", ]
} else if(specifications$test_sit[i] == "group") {
  dat <- dat[dat$testsit == "group", ]
}

# horizontal_ref
if(specifications$horizontal_ref[i] == "yes") {
  dat <- dat[dat$horizontal == "yes", ]
} else if(specifications$horizontal_ref[i] == "no") {
  dat <- dat[dat$horizontal == "no", ]
}

# vessel_shape
if(specifications$vessel_shape[i] == "rectangular") {
  dat <- dat[dat$vessel == "rectangular", ]
} else if(specifications$vessel_shape[i] == "other_shape") {
  dat <- dat[dat$vessel == "other", ]
}

# remove rows with missing effect size or variance
if (specifications$effect[i] == "d") {
  dat <- dat[!is.na(dat$d) & !is.na(dat$d_Var), ]
} else if (specifications$effect[i] == "g") {
  dat <- dat[!is.na(dat$g) & !is.na(dat$g_Var), ]
}

# only compute meta-analytic summary effects for specification subsets with at least two
studies/samples.
if(nrow(dat) < 2) next

# troubleshooting: check dat$id
print(dat$id)

# Save which study/sample IDs were selected by the "Which" factors for a given
specification.
#specifications$set[i] <- paste(rownames(dat), collapse = ",")
specifications$set[i] <- paste(dat$id, collapse = ",")
##########################################################################
#### Determine specification analyses by using "How" factors ##########
##########################################################################
if(specifications$effect[i] == "d") {
```

```
    if(specifications$ma_method[i] == "FE") {
      mod <- rma(yi = dat$d, vi = dat$d_Var, method = "FE")
    } else if(specifications$ma_method[i] == "REML") {
      mod <- rma(yi = dat$d, vi = dat$d_Var, method = "REML", control = list(stepadj = 0.5,
maxiter = 2000))
    }
    specifications$mean[i] <- mod$b[[1]]
    specifications$lb[i] <- mod$ci.lb[[1]]
    specifications$ub[i] <- mod$ci.ub[[1]]
    specifications$p[i] <- mod$pval[[1]]
    specifications$k[i] <- nrow(dat)
    ##################################################
  } else if(specifications$effect[i] == "g") {
    if(specifications$ma_method[i] == "FE") {
      mod <- rma(yi = dat$g, vi = dat$g_Var, method = "FE")
    } else if(specifications$ma_method[i] == "REML") {
      mod <- rma(yi = dat$g, vi = dat$g_Var, method = "REML", control = list(stepadj = 0.5,
maxiter = 2000))
    }
    specifications$mean[i] <- mod$b[[1]]
    specifications$lb[i] <- mod$ci.lb[[1]]
    specifications$ub[i] <- mod$ci.ub[[1]]
    specifications$p[i] <- mod$pval[[1]]
    specifications$k[i] <- nrow(dat)
  }
}
# Only keep specifications with at least 2 studies/samples
specifications_full <- specifications[complete.cases(specifications),]
# Only keep unique study/sample subsets resulting from "Which" factor combinations.
specifications_full <- specifications_full[!duplicated(specifications_full[, c("mean", "set",
"ma_method", "effect")]), ]
# Indicator if all studies are included in the set
specifications_full$full_set <- as.numeric(specifications_full$set == paste(1:nrow(x), collapse
=",", sep = ""))

# Save specification data
write_xlsx(specifications_full, path =
"/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/specifications_final.xlsx")

### Inspect data

# get descriptives
summary(specifications_full$mean, NA.rem = TRUE)

# count positive effects
```

```
pos <- sum(specifications_full$mean > 0)
pos

# count positive and significant effects
pos_and_sign <- sum(specifications_full$mean > 0 & specifications_full$p < 0.05)
pos_and_sign

# see if there were negative or zero and significant effects
neg_and_sign <- sum(specifications_full$mean <= 0 & specifications_full$p < 0.05)
neg_and_sign


## Descriptive specification curve

# prepare plotting data for tile plot
# grouping factors
author_sex <- c("male", "female", "total_sex")
age_group <- c("children", "adolescents", "adults", "total_age")
sample_type <- c("undergraduate students", "other_sample", "total_sample")
origin <- c("North America", "other_origin", "total_origin") # "Greece", "Australia", "Italy", "Oman", "Norway", "Netherlands", "Austria", "Singapore", "Switzerland", "Sweden", "India", "either")
response <- c("draw WL", "other_response", "total_response")
published <- c("published", "unpublished", "total_published")
test_sit <- c("individual", "group", "total_testsit")
horizontal_ref <- c("yes", "no", "total_ref")
vessel_shape <- c("rectangular", "other_shape", "total_shape")
# different methods
effect <- c("d", "g")
ma_method <- c("FE", "REML")

x_rank <- rank(specifications_full$mean, ties.method = "random")
yvar <- rep(factor(rev(c(author_sex, age_group, sample_type, origin, response, published, test_sit, horizontal_ref, vessel_shape, effect, ma_method)), levels = rev(c(author_sex, age_group, sample_type, origin, response, published, test_sit, horizontal_ref, vessel_shape, effect, ma_method))), times = nrow(specifications_full))
#all_factors <- c(author_sex, age_group, sample_type, origin, response, published, test_sit, horizontal_ref, vessel_shape, effect, ma_method)
#all_levels <- rev(unique(all_factors))
#yvar <- rep(factor(all_levels, levels = all_levels), times = nrow(specifications_full))
xvar <- rep(x_rank, each = length(levels(yvar)))
#xvar <- rep(x_rank, each = length(all_levels))
spec <- NULL
# Determine which specifications are observed and which are not
for(i in 1:nrow(specifications_full)) {
```

```
  id <- as.numeric(levels(yvar) %in% as.character(unlist(specifications_full[i, 2:12]))) # 2:12
because I added an ID column
  spec <- c(spec, id)
}

plotdata <- data.frame(xvar, yvar, spec)

ylabels <- rev(c("author sex: male", "author sex: female", "author sex: either",
             "age group: children", "age group: adolescents", "age group: adults", "age group:
either",
             "sample: undergraduates", "sample: other", "sample: either",
             "origin: North America", "origin: other", "origin: either",
             "response: draw", "response: other", "response: either",
             "publication: yes", "publication: no", "publication: either",
             "setting: individual", "setting: group", "setting: either",
             "reference line: yes", "reference line: no", "reference line: either",
             "shape: rectangular", "shape: other", "shape: either",
             "metric: d", "metric: g",
             "model: FEM", "model: REML"
))

plotdata$k <- rep(specifications_full$k, each = length(levels(yvar)))
plotdata$fill <- as.factor(plotdata$k * plotdata$spec)
cols <- RColorBrewer::brewer.pal(min(11, length(levels(plotdata$fill)) - 1), "Spectral")

# Create specification tile plot ------------------------------------------
p_spec <- ggplot(data = plotdata, aes(x = xvar, y = as.factor(yvar), fill = fill)) +
  geom_raster() +
  #geom_hline(yintercept = c(4, 6, 9, 12, 15, 18, 21) + 0.5) +
  geom_hline(yintercept = c(2,4, 7, 10, 13, 16, 19, 22, 25, 29, 32) + 0.5) +
  scale_x_continuous(position = "bottom") +
  scale_y_discrete(labels = ylabels) +
  scale_fill_manual(values = c("white", c(cols[floor(seq(from = 1, to = length(cols), length.out
= length(levels(plotdata$fill)) - 1))]))) +
  labs(x = "Specification number", y = "Which/How factors") +
  coord_cartesian(expand = F, xlim = c(0.5, nrow(specifications_full) + 0.5)) +
  theme_bw() +
  theme(legend.position = "none",
      axis.text = element_text(colour = "black", size = 4.5),
      axis.ticks = element_line(colour = "black"),
      axis.title = element_text(size = 8),
      plot.margin = margin(t = 5.5, r = 5.5, b = 5.5, l = 5.5, unit = "pt"))

# Create summary forest plot ------------------------------------------------------
specifications_full$xvar <- x_rank
```

```
yrng <- range(c(0, specifications_full$lb, specifications_full$ub))
ylimit <- c(yrng[1] - diff(yrng)*0.1, yrng[2] + diff(yrng)*0.1)

y_breaks_forest <- round(seq(from = round(ylimit[1], 1), to = round(ylimit[2], 1), by = 0.1),
2)
y_labels_forest <- format(y_breaks_forest, nsmall = 2)
y_breaks_forest <- c(ylimit[1], y_breaks_forest)
y_labels_forest <- c(ylabels[which.max(nchar(ylabels))], y_labels_forest)

p_forest <-
  ggplot(data = specifications_full, aes(x = xvar, y = mean)) +
  geom_errorbar(aes(ymin = lb, ymax = ub, col = as.factor(k)), width = 0, size = 0.25) +
  geom_line(col = "black", size = 0.25) +
  geom_hline(yintercept = 0, linetype = 2, size = 0.25) +
  scale_x_continuous(name = "") +
  #scale_y_continuous(name = "Summary effect (d)", breaks = y_breaks_forest, labels =
y_labels_forest) +
  scale_y_continuous(name = "Summary effect (d)", breaks = seq(-2.0, 3.5, by = 0.5), labels =
format(seq(-2.0, 3.5, by = 0.5), nsmall = 1)) +
  scale_color_manual(values = c(cols[floor(seq(from = 1, to = length(cols), length.out =
length(levels(as.factor(specifications_full$k)))))])) +
  coord_cartesian(ylim = ylimit, xlim = c(0.5, nrow(specifications_full) + 0.5), expand =
FALSE) +
  ggtitle("Sex Difference in WLT Performance") +
  theme_bw() +
  theme(legend.position = "none",
        axis.text.x = element_blank(),
        axis.ticks.x = element_blank(),
        axis.text.y = element_text(colour = c("white", rep("black", times =
length(y_labels_forest) - 1)), size = 4.5),
        axis.ticks.y = element_line(colour = c("white", rep("black", times =
length(y_breaks_forest) - 1))),
        axis.title.y = element_text(size = 8),
        panel.grid.major.x = element_blank(),
        panel.grid.minor.x = element_blank(),
        panel.grid.major.y = element_line(),
        panel.grid.minor.y = element_blank(),
        plot.margin = margin(t = 5.5, r = 5.5, b = -15, l = 5.5, unit = "pt"),
        plot.title = element_text(size = 11, hjust = 0.5, face = "bold"))

# Create subset size indicator ------------------------------------------
yrng <- range(c(2, max(specifications_full$k)))
ylimit <- c(2, max(specifications_full$k))

y_breaks_size <- round(seq(from = yrng[1], to = yrng[2], by = 40), 2)
```

```
y_labels_size <- format(y_breaks_size, nsmall = 0)
y_breaks_size <- c(ylimit[1], y_breaks_size)
y_labels_size <- c(ylabels[which.max(nchar(ylabels))], y_labels_size)
specifications_full$prop_full <- specifications_full$k/max(specifications_full$k)

p_size <-
  ggplot(data = specifications_full, aes(x = xvar, y = k)) +
  geom_area(fill = "gray35", color = "black", size = 0.25) +
  scale_x_continuous(name = "") +
  scale_y_continuous(name = "# Samples", breaks = y_breaks_size, labels = y_labels_size) +
  coord_cartesian(ylim = ylimit, xlim = c(0.5, nrow(specifications_full) + 0.5), expand = FALSE) +
  theme_bw() +
  theme(legend.position = "none",
        axis.text.x = element_blank(),
        axis.ticks.x = element_blank(),
        axis.text.y = element_text(colour = c("white", rep("black", times = length(y_labels_size) - 1)), size = 4.5),
        axis.ticks.y = element_line(colour = c("white", rep("black", times = length(y_breaks_size) - 1))),
        axis.title.y = element_text(size = 8),
        panel.grid.major.x = element_blank(),
        panel.grid.minor.x = element_blank(),
        panel.grid.major.y = element_line(),
        panel.grid.minor.y = element_blank(),
        plot.margin = margin(t = 5.5, r = 5.5, b = -15, l = 5.5, unit = "pt"))

# Combine specification tile plot, subset size indicator and forest plot --------------------------------------
p <- gridExtra::arrangeGrob(p_spec, p_size, p_forest,
layout_matrix = matrix(c(3, 3, 3, 2, 1, 1, 1, 1, 1), ncol = 1))
p <- ggpubr::as_ggplot(p)

# align outlines of all plots
p <- p_forest / p_size / p_spec + plot_layout(heights = c(4.5, 1.5, 8))

ggsave("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/spec_curve_final.png", p, width = 16*1.2, height = 12*1.2, dpi = 600, units = "cm")
```

Inferential specification curve

```
## Prepare dataset

# Parametric bootstrap test: assume all study features and sample sizes are NOT random. For each study draw a new effect size z
```

```
# from a normal distribution with expected value 0 and variance 1/(N-3). To obtain r use
inverse of fisher transfrom tanh(z)
# The SE is computed as sqrt(1/(x$N-3)) for fisher's z and(1-x$r^2)*(1/sqrt(x$N-3)) for r.
# Repeat this iter times. For each iter conduct the specification analysis and save the resulting
specification curve.
# Test null hypothesis against the 1-alpha/2 and alpha/2 quantile of these iter sorted
specification curves

# load data for specification curve analysis
#dat_WLT <-
read_excel('/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/Multiverse_dataset_f
inal.xlsx')
dat_WLT <- multiverse_data   # comment out if data are loaded
###### edit: only include complete rows (including d and g)
dat_WLT <- dat_WLT[!is.na(dat_WLT$g) & !is.na(dat_WLT$g_Var), ]
###### edit: add consecutive row ID
dat_WLT$id <- 1:nrow(dat_WLT)
## load unique specification study subsets found via the "Which" factors
#sets <-
as.vector(unique(read_excel('/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/spe
cifications_final.xlsx')$set))
sets <- as.vector(unique(specifications_full$set))   # comment out if data are loaded
sets <- lapply(strsplit(sets, ","), as.numeric)
str(sets)
# Number of specifcations (number of unique study subsets times number of How Factor
Combinations)
no_spec <- length(sets) * 4
no_spec
# Number of iterations
iter <- 1000 # change back to 1000
# Matrix to save bootstrapped specification curves
res <- matrix(numeric(iter * no_spec), ncol = iter)
# Function that takes the ids of studies for each unique specification regarding the included
studies (Which factors),
# and computes the resulting summary effect for each of the 4 "How factors".

#### when using the full dataset, the missing g and g_Var rows create a problem!

spec_list  <- function(ids, data) {
  temp <- data[ids, ]
  spec <-
    c(rma(yi = d, sei = d_Var, method = "FE", data = temp)$b[[1]],
      rma(yi = d, sei = d_Var, method = "REML", control = list(stepadj = 0.5, maxiter = 2000),
data = temp)$b[[1]],
      #rma(yi = z, sei = z_se, method = "FE", weights = 1/nrow(temp), data = temp)$b[[1]],
```

```
    rma(yi = g, sei = g_Var, method = "FE", data = temp)$b[[1]],
    rma(yi = g, sei = g_Var, method = "REML", control = list(stepadj = 0.5, maxiter = 2000),
data = temp)$b[[1]]
   )
  spec
}
# Loop to draw specification curves under the null hypothesis iter times
for(j in 1:iter) {
  # Draw randomly new effect sizes (Cohen's d) from a normal distribution with SD
sqrt(d_Var)
  # and expectation 0 for each study in the data set

  # Simulate Cohen's d values under the null (mean = 0), using the known variance
  dat_WLT$d <- rnorm(nrow(dat_WLT), mean = 0, sd = sqrt(dat_WLT$d_Var))

  # Store the sorted summary effects for each specification (i.e. the null specfaction curves)
  res[, j] <- sort(unlist(lapply(sets, FUN = function(x) spec_list(x, data = dat_WLT))))
}
# Compute the 2.5% and 97.5% quantile of all specifiaction curves for each position as
reference
boot_lb <- apply(res, 1, function(x) {quantile(x, probs = 0.025)})
boot_ub <- apply(res, 1, function(x) {quantile(x, probs = 0.975)})

# Save bootstrap upper and lower limits together with the observed specification curve
boot_WLT <- data.frame(xvar = 1:no_spec, obs =
sort(read_excel('/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/specifications_fi
nal.xlsx')$mean), boot_lb, boot_ub)
write_xlsx(boot_WLT, path =
"/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/bootspec_final.xlsx")

## Plot inferential spec curve

# Load data (uncomment if boot_WLT was not created)
#plotdata_WLT <-
read_excel('/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/bootspec_final.xlsx')
plotdata_WLT <- boot_WLT   # comment out if data are loaded
# plot
p_bootspec_R <-
  ggplot(data = plotdata_WLT, aes(x = xvar, y = obs)) +
  geom_ribbon(aes(x =  xvar, ymin = boot_lb, ymax = boot_ub), fill = "gray", color = "black",
lty = "dotted", alpha = 0.7, size = 0.25) +
  geom_line(col = "#A71C49", size = 0.5) +
  geom_hline(yintercept = 0, linetype = 2, linewidth = 0.25) +
  scale_x_continuous(name = "Specification number") +
  scale_y_continuous(name = "Summary effect") +
  ggtitle("Sex Difference in WLT Performance") +
  coord_cartesian(xlim = c(0.5, nrow(plotdata_WLT) + 0.5), expand = FALSE) +
```

```
  theme_bw() +
  theme(legend.position = "none")

ggsave("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/bootspec_plot_final.png",
width = 22, height = 16, dpi = 600, units = "cm")
```

p-value histogram

```
breaks <- seq(from = 0, to = 1, by = 0.05)

# Load data (uncomment if not already done)
#specifications_full <-
read_excel('/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/specifications_final.
xlsx')

# edit: print percentages of p < .05 and p < .01
p_vals <- specifications_full$p
perc_below_05 <- mean(p_vals < 0.05, na.rm = TRUE) * 100
perc_below_01 <- mean(p_vals < 0.01, na.rm = TRUE) * 100
# print
cat("Percentage of p-values < .05:", perc_below_05, "\n")
cat("Percentage of p-values < .01:", perc_below_01)

height <- as.numeric(prop.table(table(cut(specifications_full$p, breaks))))
plotdata <- data.frame(height, breaks = breaks[-21] + 0.025)
p_R <- ggplot(data = plotdata, aes(x = breaks, y = height)) +
  geom_bar(stat = "identity", width = 0.05, color="black", fill = "#0063A6") +
  geom_bar(aes(x = breaks, y = ifelse(breaks < 0.05, height, 0)), col = "black", fill =
"#A71C49",
          stat = "identity", width = 0.05) +
  coord_cartesian(xlim = c(-0.01, 1.01), ylim = c(0, 0.15), expand = F) +
  theme_bw()  +  labs(y = "Proportion", x = "Specification p-values") +
  ggtitle("p Value Distribution") +
  theme(strip.text.x = element_text(face="bold"),
       #axis.title.x = element_text(color = "white"), # this is only necessary in case of multiple
histograms
       strip.background = element_rect(colour=NA, fill=NA),
       panel.background = element_rect(colour = "black"),
       plot.margin = margin(t = 5.5, r = 9.5, b = 5.5, l = 5.5, "pt"))

ggsave("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/p_hist_final.png", width =
8, height = 16, dpi = 600, units = "cm")
```

Combinatorial meta-analysis

```
## Preparations (uncomment if not already done)
```

```
# x <-
read_xlsx("/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/MetaAnalysis_datase
t_WLT.xlsx", sheet = 1)

## get influential cases

# Perform  random-effects meta-analysis
#res <- rma(x$d, x$d_Var, method = "REML")
#summary(res)

# perform influence analysis
#inf <- influence(res)

# get IDs of leverage points
lev_ids <- which(inf$is.infl)
lev_ids
```

GOSH plot

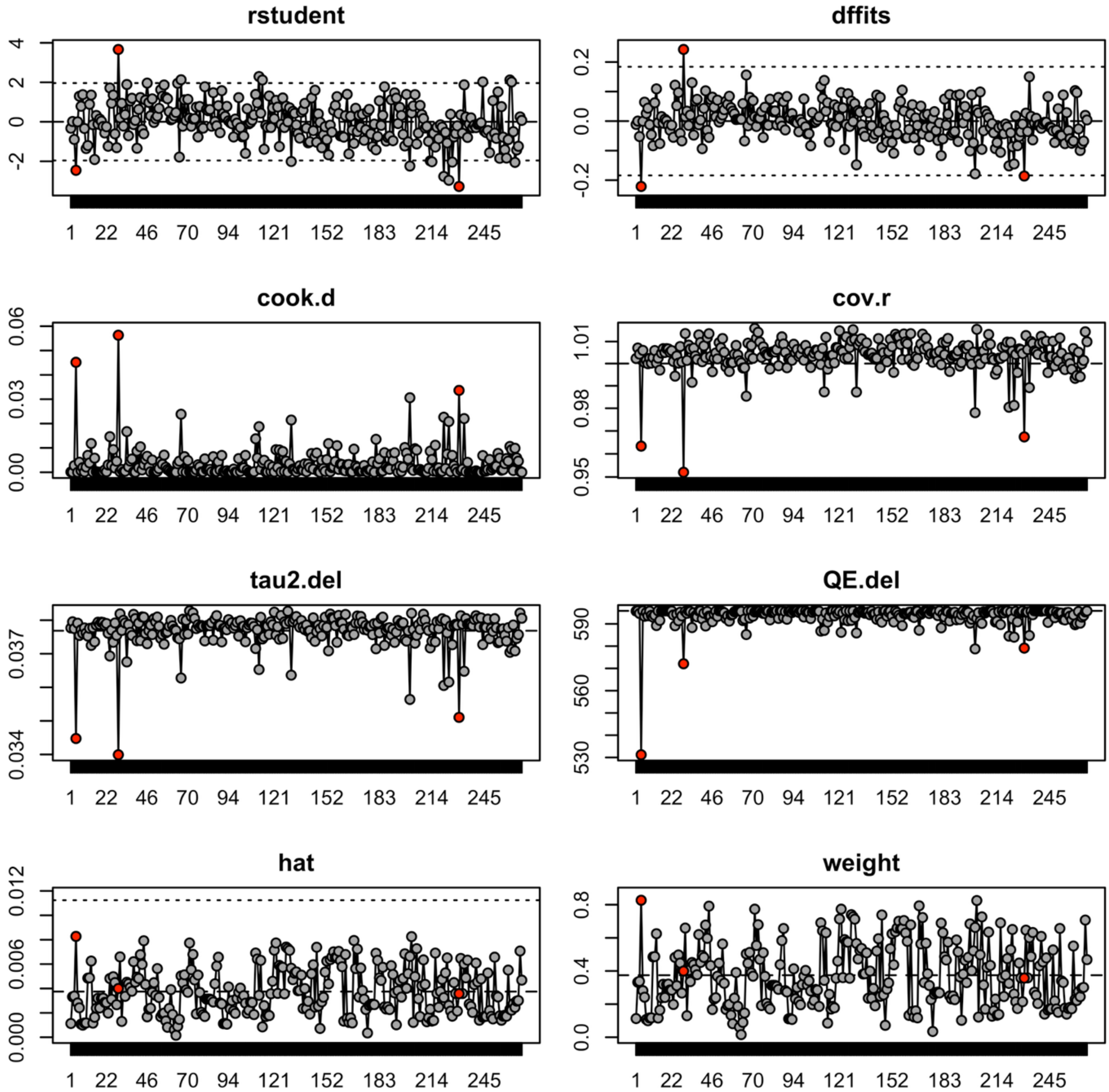
```
# source function
source("/Users/florencedejardin/Desktop/Masterarbeit/sca_gosh_Dejardin.R")

# perform combinatorial meta-analysis
gosh_new <- sca_gosh(x = cbind(x$d, sqrt(x$d_Var)), highlightID = lev_ids,
random_samples = 100000, pointsize = 0.5,
                 trans_function = NULL, x_breaks = seq(-0.2, 1.0, by = 0.2),
                 cols = c("#0063A6", "#A71C49"), xlab = "Summary effect (d)", text_size = 2.5,
x_limit = c(-0.2, 1.0))

# create plot
gosh_plot_new <- gosh_new + ggtitle("Gosh Plot")
ggsave("/Users/florencedejardin/Desktop/Masterarbeit/plots_final/gosh_final.png", plot =
gosh_plot_new, width = 7.5, height = 7.5, dpi = 1200, units = "cm")

## Get descriptives

# extract plot data
plotdata <- gosh_new$data
str(plotdata)

# save data
write_xlsx(plotdata, path =
"/Users/florencedejardin/Desktop/Masterarbeit/datasets_final/GOSH_data.xlsx")

# extract summary effects from GOSH object
effects_new <- plotdata$M
summary(effects_new)

# extract I² values from GOSH object
I2_values_new <- plotdata$I2
summary(I2_values_new)
```

Appendix G

Influence Diagnostics

Figure S1

Results of Influence Diagnostics.



Appendix H

Cumulative Meta-Analysis According to Publication Year

Figure S2

Cumulative Forest Plot.