Is Developmental Language Disorder Associated with Slower Processing Speed across Domains?

Nicole M. Zapparrata, Patricia J. Brooks, and Teresa M. Ober

1. Introduction

Information processing speed, measured via reaction or response time (RT) tasks, has been linked to individual differences in language development outcomes (Kautto et al., 2021; Marchman & Fernald, 2008). Processing speed also appears to be related to memory span and other aspects of working memory (Kail & Park, 1994; Leonard et al., 2007), fluid intelligence (Fry & Hale, 1996; Kail, 2000), and reasoning ability (Kail et al., 2016). Given the potentially far-reaching consequences of slow processing speed on cognitive development, researchers have asked whether RT measures might serve as reliable indicators of developmental delays (Kaat et al., 2022; Kibby et al., 2019; Park et al., 2015).

Across studies spanning nearly 40 years, children with Developmental Language Disorder (DLD) have exhibited longer RTs as compared to age-matched neurotypical children (e.g., Ebert, 2021; Leonard et al., 1983). Such findings led to the generalized slowing hypothesis (Kail, 1994)—an early effort to characterize the longer RTs of children with language impairment (previously called Specific Language Impairment or SLI) in terms of a domain-general deficit, as opposed one specific to language processing (van der Lely, 2005; Marinis & van der Lely, 2007). Under this hypothesis, children with DLD tend to process information more slowly than their peers across domains and tasks, including simple RT and motor skills tasks that place minimal demands on linguistic abilities (Hill, 2001). Yet, despite a considerable body of research on the subject, there has not been a comprehensive meta-analysis evaluating evidence of slower processing as a domain-general characteristic of DLD.

Windsor et al. (2001) conducted an early review of RT studies involving children with DLD, which focused on the statistical methods used to compare processing speed across groups (e.g., Brinley plots). Based on an analysis of the available data, they urged caution in interpreting evidence of generalized slowing. In the intervening decades since publication of this review, there have been major

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* Nicole M. Zapparrata and Patricia J. Brooks are at The College of Staten Island and the Graduate Center, CUNY. Teresa M. Ober is at the University of Notre Dame. Please direct correspondence to Nicole Zapparrata at nzapparrata@gradcenter.cuny.edu. The authors thank Dr. David Rindskopf for statistical consultation. The research was supported by a Doctoral Student Research Grant from the Graduate Center, CUNY. Zapparrata received the Paula Menyuk Award from BUCLD.

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advancements in meta-analytic methods, specifically robust variance estimation (RVE), a technique that weights effect size estimates based on sample size and precision to compute the standardized mean difference (e.g., *Hedges's g*). RVE makes no assumptions about the form of the sampling distribution of the effect size estimates, and requires no assumptions about the covariance between studies and effect size estimates (Hedges et al., 2010). Thus, it handles inclusion of dependent effect size estimates (Tanner-Smith & Tipton, 2014)—a common occurrence in clinical research when individuals complete multiple assessments and/or participate in multiple studies (e.g., longitudinal designs).

In recent years, there has been renewed interest in the idea that slower processing might serve as a clinical marker for children with language impairment (Park et al., 2015, 2020), in part due to difficulties in diagnosing DLD in linguistically diverse populations. Tests used to diagnose DLD have been standardized for only a small proportion of the world's languages, and generally lack norms for multilingual speakers and speakers of non-standard dialects (Kohnert, 2010; Morgan et al., 2017). Ebert and Pham (2019) found that nonlinguistic processing tasks could assist in identifying children with DLD based on an analysis of RT data from monolingual speakers of English, bilingual speakers of Spanish and English, and monolingual speakers of Vietnamese.

1.1. Research Aims

The current meta-analysis aimed to find out whether slower processing in DLD is domain-general or, alternatively, more evident on tasks requiring processing of linguistic and/or auditory stimuli or requiring a verbal response, as predicted by domain-specific accounts (Miller, 2011; van der Lely, 2005). Given evidence of impaired inhibitory control and cognitive flexibility in DLD (Pauls & Archibald, 2016), we used restrictive inclusion criteria to eliminate complex RT tasks. Hence, we based our meta-analysis on studies with simple and choice RT tasks, naming tasks, and congruent/baseline conditions of interference control tasks. Using meta-regression analyses, we sought to find out whether effect size estimates differed as a function of task type, stimulus type (linguistic vs. nonlinguistic), stimulus modality (auditory vs. non-auditory), response modality (verbal vs. nonverbal), and participant age. As a further test of generalized slowing, we used subgroup analyses to find out whether statistically significant group differences held across the subcategories within each moderator (task type, stimulus type, stimulus modality, response modality). If children with DLD have longer RTs than age-matched peers, regardless of variation in linguistic or auditory task demands, it would provide strong evidence of generalized slowing.

2. Method

2.1. Systematic Review

The meta-analysis was pre-registered on PROSPERO as part of a broader meta-analytic study of processing speed in relation to developmental disorders (Zapparrata & Brooks, 2020). Figure 1 shows the PRISMA flow diagram outlining the selection criteria for the systematic literature review and article screening process. ProQuest was searched periodically from January 2021 until May 2021. Boolean searches were conducted using multiple combinations of terms: *language impairment, Developmental Language Disorder, Specific Language Impairment, DLD, SLI, reaction time, RT, response time, naming, interference control*. Reference sections of two review articles were searched for relevant studies (Kohnert & Windsor, 2004; Windsor et al., 2001) and a forward search of citations used two key studies (Kail, 1994; Miller et al., 2001). Authors were contacted if any statistics were needed to calculate effect size estimates.

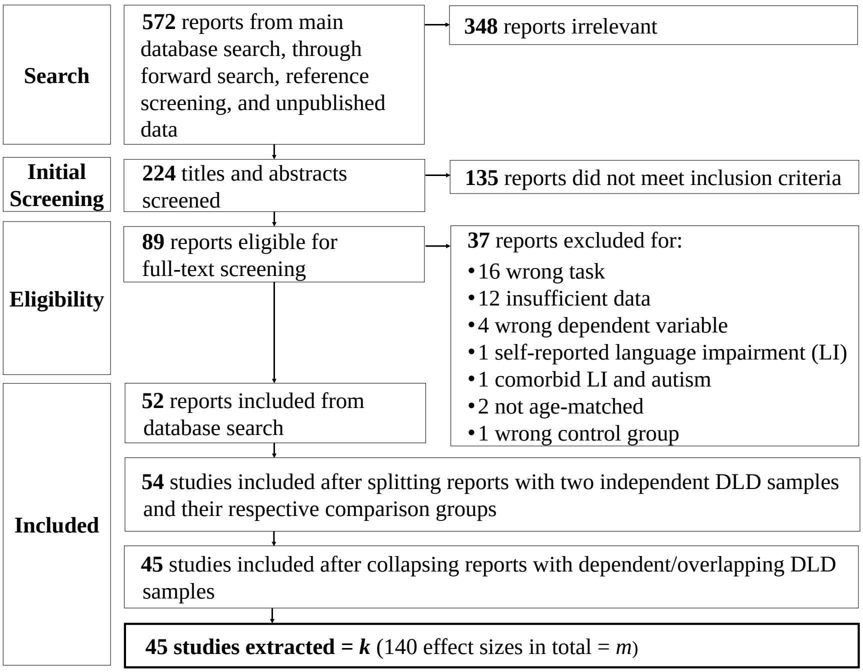

Fig. 1. PRISMA chart of systematic review

Studies had to contain data from at least one of the following general task types: simple RT, choice RT, naming, or interference-control with a congruent or baseline condition. Each included study used a task that required participants to process stimuli and make a timed verbal or nonverbal response, with RT (described as either reaction time or response time) serving as the dependent variable. Studies that used standardized scores as the dependent variable or reported the mean numbers of responses elicited during a timed interval were excluded. We also excluded studies that measured processing speed or saccades using an eye-tracking device.

Studies had to include a clinical group with DLD, also referenced in the literature as *specific language impairment, non-specific language impairment,* *language disorder, primary language impairment,* and *receptive and/or expressive language impairment*. Studies had to include a chronologically age-matched neurotypical group. Studies could match individual participants on age, match groups of participants on age, use groups with the same mean age or groups that did not differ statistically in age, or use a restricted age range to match groups on the basis of age. Table 1 lists the data sources from which we extracted the effect size estimates included in the meta-analysis.

Table 1. Relevant reports identified through the systematic review

Author Information	
Almodovar (2014)	Miller et al. (2001), (2006)
Bavin et al. (2005)	Montgomery & Leonard (1998), (2006)
Brooks et al. (2012), (2014), (2015)	Montgomery & Windsor (2007)
Coady (2013)	Montgomery (2002), (2005), (2006), (2008)
Crosbie et al. (2004)	Oram Cardy et al. (2010)
Cummings & Čeponienė (2010)	Park et al. (2020)
Davidson (1998)	Pizzioli & Schelstraete (2013)
Ebert et al. (2019), (2021)	Riddle (1992)
Edwards & Lahey (1996)	Seiger-Gardner & Brooks (2008)
Ford & Milosky (2008)	Sheng & McGregor (2010)
Garrity (2007)	Spaulding (2010)
Gelfand (2015)	Spaulding et al. (2008)
Hanson & Montgomery (2002)	Street (2005)
Hedenius et al. (2011)	Thordardottir et al. (2011)
Hennessey et al. (2010)	Tropper (2009)
Jongman et al. (2017)	Velez & Schwartz (2010)
Kail (1986)	Victorino & Schwartz (2015)
Kuntz (2012)	Weismer & Hesketh (1996), (1998)
Ladányi & Lukács (2016), (2019)	Windsor & Hwang (1999)
Lahey & Edwards (1996)	Yang & Gray (2017)
Leonard et al. (1983)	
Lum et al. (2010)	

The systematic review yielded 52 relevant reports comprising 45 studies (k) with 140 effects (m). As will be described in more detail below, reports involving the same or overlapping samples were counted as a single study. The mean age of the DLD samples ranged from 4.3 to 22.7 years (*Mean* = 8.9 years; *Median* = 8.6 years). Due to the use of the same or overlapping participant samples across reports, it is not possible to determine with any certainty the total number of participants involved. We can conservatively estimate that were at least 875 participants in the DLD groups and at least 925 participants in the age-matched neurotypical groups.

2.2. Moderator Coding

2.2.1. Task Type

Task type was coded as a factor with four levels: simple RT, choice RT, naming, and interference control (congruent/baseline conditions only). These four task types were the least complex measures of processing speed widely used in studies of DLD. We excluded RT tasks that place considerable demands on metalinguistic awareness, executive functioning, and/or statistical learning abilities (e.g., grammaticality judgment, truth-value judgment, mental rotation, memory scanning, and sequence learning). For interference control tasks (e.g., flanker, Go/No-Go, Stroop, picture-word interference, picture-picture interference, and other cross-modal interference paradigms), we extracted RTs from congruent or baseline trials only (i.e., where there was no conflict between the stimulus and the associated response).

Simple RT tasks required participants to make a specific motor response to a stimulus. Task instructions stated that when the participant saw or heard the stimulus, they should make the specified response. Simple RT tasks did not require the participant to make a choice between stimuli, match or categorize them. Choice RT tasks required the participant to evaluate one or more relatively simple stimuli and make a forced-choice response. Naming tasks were operationally defined as tasks that required the participant to verbally name visual stimuli presented to them as quickly and accurately as possible. Interference control tasks were operationally defined as tasks that involve attentional control, i.e., responding to a visual or auditory target while ignoring a distractor, responding to a target preceded by a priming stimulus, or withholding a response to non-target stimuli and only responding to targets. The tasks included in this subgroup included variations of flanker, go/no-go, Stroop, picture-word interference, picture-picture interference, and cross-modal recognition tasks. To minimize inhibitory demands, we extracted RTs only from baseline (aka "neutral") or congruent conditions, where there was no conflict between the stimulus and the response. Baseline conditions were preferred over congruent conditions when available.

2.2.2. Stimulus Type, Stimulus Modality, and Response Modality

Stimulus type was coded as a two-level factor: linguistic vs. nonlinguistic. Shapes, figures, colors, and objects were categorized as nonlinguistic stimuli. Linguistic stimuli could be presented auditorily or visually, and included single digits, single letters, digit/letter strings, words, and pseudowords used as targets, primes, or distractors. Note that the stimulus had to be either a target or a prime/distractor to be coded as linguistic. Thus, if a nonverbal task began trials with a signal word, such as *Ready* or *Start*, or ended with a word such as *Stop*, extracted effects were *not* coded as linguistic (e.g., Oram Cardy et al., 2010).

Stimulus modality was coded as a two-level factor: auditory vs. non-auditory. Tasks were categorized as auditory if target, prime, or distractor stimuli were presented in the auditory modality. Tasks that did not have any auditory component (i.e., fully visual) were categorized as non-auditory. Response modality was also coded as a two-level factor: verbal vs. nonverbal. Verbal responses were operationally defined as tasks requiring a vocal response to a stimulus, e.g., saying “yes” or “no” or naming the stimulus.

2.2.3. Age

We included the age of the DLD group (mean centered) as a covariate in the analysis. Mean-centering involves taking the mean age calculated from all study effects (i.e., *grand mean* = 8.9 years) and subtracting it from the mean age associated with each individual study effect. The units of the variable and the dispersion of the distribution are retained. The new mean of the variable is 0, which renders its intercept more interpretable.

2.3. Data Extraction and Reliability

As noted previously, researchers often administered multiple measures and/or reported data from the same or overlapping samples in consecutive reports. To account for the dependency of observations, we coded for lab and treated estimates taken from consecutive reports as a single study. This was done when the researchers indicated the use of the same or overlapping samples across reports (e.g., Edwards & Lahey, 1998; Lahey & Edwards, 1986). If a report included more than one DLD sample, each compared to a separate control group, we coded them as independent studies. For example, Ebert et al. (2019), Ebert (2021), and Park and Miller (2020) included monolingual and bilingual DLD groups, each with separate control groups. Riddle (1992) split their DLD and control groups into separate older and younger groups; these were coded as independent studies. If a study included two DLD samples compared to the same neurotypical group (e.g., Miller et al., 2001, 2006), the *N* of the control group was split in half. This was done to avoid double counting participants, which artificially inflates the number of observations (Higgins et al., 2008).

If a study included multiple tasks meeting inclusion criteria, each task was extracted as a separate effect. If a study reported multiple conditions of a task meeting inclusion criteria, each condition was extracted as its own effect rather than pooling them together. This was done to avoid making the assumption that the pooled conditions create a valid overall score for a given task. For further information about study identification and extracted effects, the full dataset has been made publicly available through an OSF repository (Zapparrata et al., 2022).

Two coders (the first and third authors) independently extracted effect size estimates for 40% (k = 18) of the studies. Inter-rater reliability (92% agreement) was calculated as the proportion of extracted information in agreement out of the total amount of information extracted by the two raters. Inconsistencies were resolved by reviewing data entry and reaching consensus after correcting any clerical errors. The first author extracted the estimates for the remaining studies.

3. Results

3.1. Main Analysis

Effect size estimates (*g*) were calculated using random-effects RVE. Analyses were conducted in the *R* statistical environment using the *Metafor* (Viechtbauer, 2010) and *Robumeta* (Fisher et al., 2016) packages. The overall effect (intercept-only model) indicated significantly slower processing in DLD groups as compared to age-matched neurotypical groups (small-to-medium effect: $g = .47$, $p < .001$, 95% $CI = .38; .56$). The positive value of *g* indicates longer RTs in DLD groups. The proportion of heterogeneity (I^2) attributed to true differences between the studies was 20%. Publication bias was examined with funnel plots using Egger's test (Egger et al., 1997), which did not provide any evidence of publication bias ($z = 1.63$, $p = .10$). We also performed a sensitivity analysis to determine that coefficients and their standard errors were consistent across different values of *rho*. The results shown use a *rho* of 0.8. The datafile and R analysis script are available in our OSF repository (Zapparrata et al., 2022).

3.2. Moderator Analysis

Meta-regression analyses were used to find out whether effect size estimates varied across levels of each moderator (i.e., task type, stimulus type, stimulus modality, response modality, age). Task type (simple RT, choice RT, naming, interference control), stimulus type (linguistic vs. nonlinguistic), response modality (verbal vs. non-verbal), and age (grand-mean centered) were not significant.

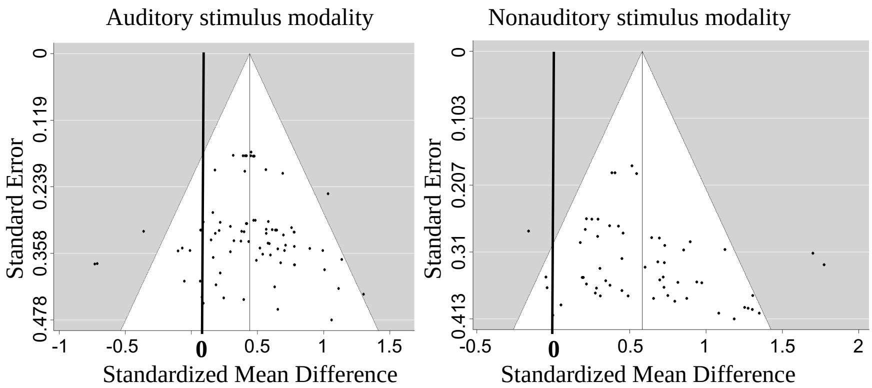

Figure 2. Funnel plots of effect size estimates for stimulus modalities

Stimulus modality (auditory vs. non-auditory) was statistically significant, $\beta = -.17$, *95% CI* [–.34 ; –.01], $p = .04$. The coefficients indicated larger effect size estimates for tasks using only non-auditory (visual) stimuli. Figure 2 displays funnel plots of the effects for studies with auditory (left panel) and non-auditory (right panel) stimuli. The vertical line in each figure indicates a mean difference of 0. The majority of effects for both auditory and non-auditory stimuli were positive, meaning that DLD groups had longer RTs than age-matched control groups across both stimulus modality conditions.

3.3. Subgroup Analysis

To determine whether DLD and age-matched neurotypical groups differed significantly across moderator categories, we ran subgroup analyses; see Table 2, for results. The subgroup analyses involved grouping the estimates into subsets for each level of the moderator, then running separate RVE models (intercept-only) on estimates from each of the levels. For example, within the stimulus modality moderator, auditory effects were separated from non-auditory effects, with an RVE model run on each category. The subgroup analyses indicate significantly longer RTs in the DLD groups compared to age-matched groups across task types, stimulus types, stimulus modalities, and response modalities.

Table 2. Subgroup analyses for each moderator category

		Summary Statistics		
Moderator	*k, m*	*g (SE)*	*95 % CI*	*p-value*
Task Type				
Simple RT	*k* = 22, *m* = 53	.44 (.07)	[.30; .58]	< .001
Choice RT	*k* = 11, *m* = 18	.55 (.08)	[.37; .74]	< .001
Naming	*k* = 12, *m* = 25	.70 (.14)	[.40; 1.01]	< .001
Interference Control	*k* = 15, *m* = 44	.39 (.05)	[.27; .50]	< .001
Stimulus Type				
Linguistic	*k* = 16, *m* = 46	.44 (.10)	[.23; .64]	< .001
Nonlinguistic	*k* = 35, *m* = 94	.50 (.05)	[.40; .60]	< .001
Stimulus Modality				
Auditory	*k* = 28, *m* = 82	.39 (.05)	[.28; .50]	< .001
Nonauditory	*k* = 24, *m* = 58	.55 (.06)	[.43; .67]	< .001
Response Modality				
Verbal	*k* = 19, *m* = 70	.58 (.08)	[.42; .75]	< .001
Nonverbal	*k* = 30, *m* = 70	.41 (.06)	[.30; .53]	< .001

4. Discussion

The current meta-analysis synthesized research on processing speed in DLD with the aim of reevaluating evidence of generalized slowing of information processing across tasks and domains (Kail, 1994; Windsor et al., 2001). We focused our systematic review on relatively simple measures of processing speed that required either a verbal or nonverbal (motor) response, with the goal of determining whether slower processing was evident across tasks varying in linguistic and auditory processing requirements. The results indicated significantly longer RTs in DLD groups compared to age-matched neurotypical groups, with the overall estimate (g = .47, 95% CI: .38; .56) indicating a small-to-medium effect. Under the hypothesis that deficits associated with DLD are specific to language (Marinis & van der Lely, 2007; van der Lely, 2005), we would expect larger differences between DLD groups and age-matched neurotypical groups when tasks relied on linguistic stimuli and/or verbal responses. Yet we found no evidence that either stimulus type or response modality moderated effects. The only moderator to reach statistical significance was stimulus modality, where the coefficients indicated a smaller difference between DLD groups and age-matched groups when tasks used auditory as compared to non-auditory (i.e., fully visual) stimuli. This finding runs counter to auditory processing theories of DLD (Corriveau et al., 2007; Miller, 2011), which focus on the atypical processing of acoustic information and sound patterns in individuals with DLD.

The subgroup analyses confirmed significantly longer RTs in DLD groups relative to age-matched neurotypical groups across all task types, stimulus types, stimulus modalities, and response modalities—providing the strongest evidence to date for generalized slowing in DLD. These findings complement and extend other meta-analyses documenting domain-general (or nonlinguistic) impairments in DLD: Ebert and Kohnert (2011) on sustained attention, Obeid et al. (2016) on statistical learning, Vugs et al. (2013) on visual-spatial working memory, and Pauls and Archibald (2016) on inhibition and cognitive flexibility, with the latter meta-analysis also finding no evidence that linguistic task demands moderated effects. We do not yet know which constructs have the greatest validity in predicting language development outcomes. This will require longitudinal research; for example, Kautto et al. (2021) reported that processing speed was a better predictor of subsequent language outcomes for late talkers than measures of inhibitory control. Research is also needed to ascertain how slower processing speed relates to underlying brain systems, as in the procedural deficit hypothesis of DLD (Ullman & Pierpont, 2005). Additionally, given that most RT tasks require a verbal or motor response, research is needed to disentangle generalized slowing in DLD from impaired motor skills (Hill, 2001).

Including nonverbal processing speed measures in clinical assessment may ameliorate difficulties associated with establishing equivalence of verbal tests (e.g., nonword repetition, sentence repetition, and grammaticality judgement) used as clinical markers of DLD (Park et al., 2015). This may assist in diagnosis of DLD in multilingual children, dialect speakers, and speakers of minority languages for whom there is a paucity of validated tests (Garraffa et al., 2019; Morgan et al., 2017). However, slow processing is unlikely to differentiate DLD from other developmental disorders, as it is implicated in other disorders, e.g., attention deficit hyperactivity disorder (ADHD) (Kibby et al., 2019; Oram Cardy et al., 2010), that have high comorbidity with DLD (Mueller & Tomblin, 2012). Notably, Gooch et al. (2019) found processing speed to be a better predictor of language outcomes over time when attentional difficulties accompanied DLD. The current findings also have therapeutic implications for addressing slower processing speed in children with DLD. Processing speed interventions have demonstrated success in improving children's RTs (Ebert et al. 2012; Mackey et al., 2011), but more research is needed to ascertain their effectiveness. In the meantime, giving children with DLD extra time to complete assignments may be a relatively simple way to support their development in academic contexts (Gernsbacher et al., 2020).

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