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Lexical Access Speed and the Development of Phonological Recoding during Immediate Serial Recall

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ABSTRACT

A recent Registered Replication Report (RRR) of the development of verbal rehearsal during serial recall revealed that children verbalized at younger ages than previously thought, but did not identify sources of individual differences. Here, we use mediation analysis to reanalyze data from the 934 children ranging from 5 to 10 years old from the RRR for that purpose. From ages 5 to 7, the time taken for a child to label pictures (i.e. isolated naming speed) predicted the child's spontaneous use of labels during a visually presented serial reconstruction task, despite no need for spoken responses. For 6- and 7-year-olds, isolated naming speed also predicted recall. The degree to which verbalization mediated the relation between isolated naming speed and recall changed across development. All relations dissipated by age 10. The same general pattern was observed in an exploratory analysis of delayed recall for which greater demands are placed on rehearsal for item maintenance. Overall, our findings suggest that spontaneous phonological recoding during a standard short-term memory task emerges around age 5, increases in efficiency during the early elementary school years, and is sufficiently automatic by age 10 to support immediate serial recall in most children. Moreover, the findings highlight the need to distinguish between phonological recoding and rehearsal in developmental studies of short-term memory.

Short-term and working memory skills improve markedly throughout early and middle childhood. However, the extent to which this improvement is due to increased capacity, increased processing speed, and the development of specific strategies is debated (Camos &

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Barrouillet, 2011; Cowan, 2016; Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011; Fry & Hale, 2000; Jarrold & Tam, 2011). In particular, the continuing development of language skills during childhood may support the use of more complex verbal strategies during short-term and working memory tasks (Nation & Hulme, 2011). Understanding the developmental trajectories of different strategies – independent of changes to capacity and processing efficiency – is crucial because strategy use is likely the best candidate for intervention (St Clair-Thompson, Stevens, Hunt, & Bolder, 2010). Just as importantly, identifying the expected range of variability around the emergence and efficiency of these strategies – for use in standard short-term and working memory assessments – will provide context for when intervention may be necessary. Unfortunately, standard immediate serial recall – the most commonly used clinical assessment of short-term memory – does not afford the experimental control necessary to dissociate the development of different strategies from changes in capacity and processing speed. Therefore, it is difficult for clinicians to identify age-appropriate targets for intervention when serial recall performance is poor. Fortunately, various measures of speech output timing have been used to isolate the language skills which might serve as foundations for verbal short-term and working memory strategies.

The current study uses one such measure, namely isolated naming, to assess the contribution of speeded lexical access to the phonological strategies of recoding and rehearsal which, in turn, support serial recall. Importantly, by reanalyzing data from a very large sample of children, these relationships could be examined across childhood in order to articulate the general developmental trajectory of these phonological strategies as well as the individual differences that underly variability around their development. First, we will describe the benefits of efficient phonological strategy use in adulthood. We then provide a recently updated developmental timeline noting the emergence of phonological strategies as tapped in standard short-term and working memory tasks during development. Finally, we propose isolated naming speed as a measure of individual differences in the efficiency of phonological strategy use. This proposal stems from the reading development literature which suggests that lexical access speed – as measured by isolated naming speed – constrains reading skill in early readers, but variability in lexical access speed decreases during development. Therefore, other general processing skills become better predictors of that domain of cognition across later stages of development.

Labeling supports phonological strategies in adulthood

The seemingly simple skill of rapidly saying the name of a visual symbol is related to a variety of higher order abilities including reading (Wolf & Bowers, 1999), executive function (AuBuchon, Pisoni, & Kronenberger, 2015), and even behavior regulation (Tannock, Martinussen, & Frijters, 2000). The emergence of verbal labeling as a mnemonic strategy is also thought to underlie a developmental improvement in serial recall, even when responses are not spoken but are instead pointed to (Elliott et al., 2021; Flavell, Beach, & Chinsky, 1966). In particular, efficient verbal labeling is likely a foundational skill that underlies the more complex strategy of rehearsal. Adults commonly report using rehearsal – the repetition of a to-be-remembered item's phonological code – during immediate serial recall tasks (Norris, Hall, & Gathercole, 2019); this strategy appears to be effective for maintaining items when no intervening processing tasks are required (Engle, Cantor, & Carullo, 1992; Turley-Ames & Whitfield, 2003).

When memoranda are presented visually, they must be recoded into a phonological representation prior to rehearsal by assigning the item a verbal label (Conrad & Hull, 1964). Notably, in discussions around adult strategy use, this act of phonological recoding is assumed to occur covertly and via the initial rehearsal loop (Della Sala, Logie, Marchetti, & Wynn, 1991), so phonological recoding is rarely discussed as an independent strategy within the adult literature. However, labeling appears to benefit serial recall in its own right, as well as act as a precursor of rehearsal (Henry, Turner, Smith, & Leather, 1991; Poloczek, Henry, Messer, & Büttner, 2019). Therefore, before rehearsal reaches highly efficient adult-like levels, it may prove useful to dissociate verbal labeling (as an overt form of phonological recoding) from rehearsal.

The development of phonological strategies and serial recall

The developmental trajectory of children's rehearsal was first articulated by Flavell, Beach, and Chinsky in 1966. For the intervening decades, their sample of 60 children – twenty 5-year-olds, twenty 7-year-olds, and twenty 10-year-olds – largely drove claims that children begin to spontaneously rehearse at age 7 (Henry et al., 1991). Flavell et al. observed that most of the 7- and 10-year-olds consistently verbalized (i.e., produced lip movements or other behaviors indicative of phonological recoding and/or rehearsal) while attempting to recall lists of serially presented pictures; in contrast, only two of the twenty 5-year-olds verbalized at any point throughout the study. However, more recent work by Jarrold, Cocksey, and Dockerill (2008) and Jarrold & Citroen (2013) demonstrated that, after controlling for developmental changes in capacity, 5-year-old children display another behavioral marker of phonological recoding, the *phonological similarity effect*. This effect denotes the observation that it is more difficult to remember a sequence of items with shared phonemes (e.g., *map, mat, rat, ran, man*) than a sequence of items with distinct phonemes (e.g., *clock, tree, bus, door, fish*). The presence of the phonological similarity effect for visually presented lists in 5-year-old children presumably indicates that at least a considerable subgroup of 5-year-olds recoded the visual items into corresponding verbal-phonological labels during immediate serial recall.

The clear discrepancy between the phonological similarity effect data (Jarrold & Citroen, 2013) and direct observations of young children's verbalizations during serial reconstruction of picture sequences (Flavell et al., 1966) prompted a large-scale, multi-lab replication effort (Registered Replication Report [RRR]: Elliott et al., 2021) to better understand the developmental trajectory of spontaneous verbalization in the service of short-term memory. The data of this RRR were convincing: consistent with the initial conclusion of Flavell et al., verbalizations peaked in the 7-year-old-group, then held steady from age 7 to age 10. However, consistent with Jarrold and Citroen (2013) findings, a substantial subset of 5- and 6-year-olds also verbalized. Importantly, the children who were classified as verbalizers had longer maximal spans. Moreover, performance improved when children were instructed to name items aloud during list presentation. These findings by Elliott et al. (2021) highlight the need to understand individual differences that underlie the development of phonological recoding when used in support of short-term and working memory.

Isolated naming speed measures lexical access abilities

Although behavioral markers have been identified to indicate the *presence* of various short-term and working memory strategies during development, fewer reliable indices have been identified to assess changes in the ease or *efficiency* with which children use strategies. Such indices would provide a more nuanced understanding of children's strategy development. Here, we turn to the literature on reading development for reliable measures of verbal efficiency to index skills also used in short-term and working memory tasks.

Isolated naming, which serves as a proxy for the efficiency of lexical access, refers to the time taken to retrieve a label for a single object (e.g., digit, letter, color, and picture) from long-term memory and to begin the appropriate articulatory-motor program to say that label. Like other speeded responses, isolated naminng contains two potential sources of variance – processing speed and the speed of lexical/phonological retreival. Unlike other speeded responses, individual differences in isolated naming speed are driven primarily by the variability in retrieval of lexical/phonological representations.

Another type of speeded responses, rapid naming – measured by presenting the child a page of digits (or letters, or color patches, or picture of familiar objects) listed in a random order and asking the child to name all of the items as quickly as possible – is most associated with research exploring the precursors of reading (Wolf & Bowers, 1999) and is a predictor of general language ability from ages 5 to 10 years (Archibald, 2013). Notably, rapid naming becomes even more predictive of reading skill after controlling for isolated naming. This suggests that both tasks tap variability in lexical access and that rapid naming additionally taps variability in a separable skill such as processing speed (Logan, Schatschneider, & Wagner, 2011) or the coordination of multiple phonological processing tasks, including inhibition of the articulatory motor commands which were used to output prior items (Wolf & Bowers, 1999). Moreover, the relative speeds with which children can complete isolated versus rapid naming shifts across development. Kindergarten children (approximately five-and-a-half years old) are faster, per item, when items are presented in isolation; in contrast, two years later those same children are faster, per item, when those items were presented in a rapid naming task (Logan et al., 2011). Notably, rapid naming also begins to predict working memory performance around seven-and-a-half years old (Archibald, 2013). This shift in relative speeds suggests that the importance of speeded lexical access – tapped by isolated naming – as an individual difference variable may also shift across development.

Separating individual differences in speeded processing from age-related decreases in speeded processing presents statistical and methodological challenges. Speeded responses have long been used to assess general processing efficiency (Case, Kurland, & Goldberg, 1982; Cepeda, Blackwell, & Manakata, 2013; Fry & Hale, 2000). At the group level, developmental changes in a variety of these speeded measures reflect the nonlinear growth functions also observed in intelligence and working memory (Fry & Hale, 2000). By correlating group-level averages of performance at each age, these studies reveal developmental trends, but unfortunately, obscure individual differences (see Fry & Hale, 2000, for a review). In contrast, individual differences can be revealed by examining the relationships between speeded tasks and working memory within a single discrete age range or by statistically controlling for age, but these approaches make developmental trends difficult to interpret (Fry & Hale, 2000). Simultaneously assessing both individual and age-related differences between isolated naming speed and short-term/working memory would require a very large data set with sufficient sample sizes to report correlations by age group (Fry & Hale, 2000).

The predictive value of isolated naming speed on serial recall was dismissed by Hitch, Halliday, and Littler (1989) when they observed no relationship between single-item word reading and memory span for those same printed words. However, in order to utilize printed words as stimuli, the youngest children tested in their study were 8 years old. According to the results from both Flavell et al. (1966) and Elliott et al. (2021), many of these 8-year-olds should be rehearsing. Indeed, articulation rate, a common proxy for rehearsal speed (Cowan et al., 1994), was correlated to span in these 8-year-old children. Additionally, their span was disrupted when they were required to overtly count during item presentation. Notably, when rehearsal was disrupted with this method of articulatory suppression, a relationship between isolated naming speed and span emerged (Hitch et al., 1989). Taken together, these findings from Hitch et al. suggest that once children begin rehearsing, individual differences in rehearsal mask individual differences in the foundational skill of phonological recoding.

Elliott et al. (2021, p. 18) provided anecdotal evidence that speeded lexical access is a necessary precursor to phonological recoding and that this skill may contribute to individual differences in younger children's serial recall performance. They noted that, "Although we tried to remain as true as possible to the Flavell et al. (1966) study, we found that the pacing in the point-and-name task (at the rate of 2 s per item) was difficult for many of the youngest children to follow." In the original study, one manipulation asked children to name each item as the experimenters pointed to the object. Although the experimenters' goal was to point to a new object every two seconds, it is possible that they made subtle adjustments to their pointing rate in order to accommodate young children's slightly slower labeling. These adjustments could have gone unnoticed by the experimenters or have fallen within a window of acceptable variation considering the manual presentation format. The replication, however, employed a computerized presentation rate which would be unaffected by the child's labeling efficiency. Therefore, the standardized computer presentation used in the replication likely revealed subtle individual and age-related differences in lexical access speed which would not have been evident to Flavell and colleagues, given their original study design and procedure.

Current study

Despite the known benefits of phonological recoding and rehearsal in the support of memory and executive control, little is known about the individual differences that lead to the spontaneous use of these strategies across development. The current reanalysis of our RRR data directly assessed the question of whether lexical access speed is an individual difference variable that predicts spontaneous verbalization and subsequent serial recall at four ages: 5, 6, 7, and 10 years old. Though not intended as a measure of isolated naming speed, response times were incidentally collected when assessing children's ability to name each picture, one at a time, as part of the inclusion criteria of the original RRR.

Statistical and methodological limitations of prior research have hampered the simultaneous assessments of age-related changes and individual differences in speeded processing which may support short-term and working memory (Fry & Hale, 2000). By obtaining isolated naming speed from a large-scale replication, the current reanalysis allowed us to test the following predictions: (1) If efficient lexical access is a precursor to phonological recoding, then children with faster isolated naming speeds will be more likely to be classified as verbalizers. (2) The strength of the direct relationship between isolated naming speed and immediate serial recall will have a U-shape across development. Not all 5-year-olds engage in phonological recoding in the service of memory (operationalized as *verbalization*); therefore, individual differences in their recall accuracies will be reliant on individual differences in other underlying skills. Conversely, older children's lexical retrieval abilities may reach a plateau sufficient for the sequential phonological recoding of multiple memoranda; therefore, the limiting factor in their recall would shift to more complex skills. In addition to testing the two predictions outlined above, we also carried out auxiliary analyses including delayed serial recall. The extant literature does not provide clear theory to drive predictions regarding these trials.

Including verbalization status as a mediator allowed us to better understand any changes to the direct relationship between isolated naming and immediate serial recall. Because isolated naming is considered a relatively pure measure of lexical access, it should be predictive only for those children who actually apply verbal labels to the visually presented items during the memory test. Elliott et al. (2021) observed different proportions of children verbalizing at each age group, so we might expect the strength of the direct relationship between isolated naming and recall to vary across development. Isolated naming would provide no meaningful explanation of recall variance for children who are not using phonological strategies. Consequently, we might not expect a strong direct relationship between isolated naming and recall in the 5-year-old group, as nearly a quarter of 5-year-old children were not observed to verbalize. If we were only examining individual differences among 5-year-olds, the lack of a correlation between isolated naming speed and recall would be difficult to interpret. Nonetheless, even if only an indirect relationship is observed between isolated naming and recall (via verbalization), such a finding can be situated within a developmental framework, given the multiple age groups and large sample sizes. Specifically, understanding the role of verbalization as a mediator in older children will contextualize any indirect relationship in 5-year-olds that includes verbalization. If serial recall is limited by different factors (i.e., capacity, processing speed) and/or different strategies develop at different rates across development, then we would expect the predictive values of lexical access (both direct and indirect) to also change across age groups.

Method

Participants

Participants were a subsample of the primary Flavell et al. (1966) Registered Replication Report project dataset collected between January 2019 and January 2020 (Elliott et al., 2021). Individual lab protocols, noting compliance with local ethical review boards, are available at https://osf.io/pn4rk/. Because the item labeling portion of the test session was not included in the publicly available dataset, inclusion was based on participating laboratories' willingness to share their aggregated raw memory data file. The participating 16 laboratories – representing samples from the United States (N = 276), Germany (N = 190), United Kingdom (N = 99), Costa Rica (N = 78), New Zealand (N = 76), Italy (N = 55), Switzerland (N = 54), Norway (N = 51), Austria (N = 33), and Turkey (N = 27) – collected data from 939 children.[1] Children were tested in their primary language.

Isolated naming speed data was missing for one child. Four other children from the subset of provided data were excluded for the present analysis: two 10-year-old children from the same lab had median isolated naming speeds greater than 16 minutes, suggesting experimenter and/or equipment error; two other children, a 6-year-old and a 7-year-old, had median isolated naming speeds 2.5 seconds and 4 seconds longer than the other children of their age. These children were excluded after consultation with staff from the respective data collection sites. Though neither lab had notes of unexpected or unusual behavior, one lab was able to review video and confirmed that the child consistently included a carrier phrase (e.g., "I think it could be a flag"). Therefore, the final dataset for the present analysis included 934 children representing four age groups: 5 years (*N* = 210; 47% female), 6 years (*N* = 243; 51% female), 7 years (*N* = 258; 52% female), and 10 years (*N* = 223; 48% female).

Apparatus, stimuli, and procedure

Recall Task. A complete description of the recall tasks is provided in Elliott et al. (2021). Therefore, they are only briefly described here. On each trial, seven colorful drawings (an apple, a comb, a generic blue flag, a yellow flower, a moon, an owl, and a pencil) appeared in random positions within a single horizontal row on the computer screen. Items in the current list were indicated in succession by the frame around each to-be-remembered item changing color for 2 seconds. The location of the item in the row was independent of its order in the list. All children were presented two lists at each list length, beginning with a list length of 2, then increasing to 3, 4, and 5. Thus, all items appeared on the screen in all trials, but were not necessarily illuminated as a to-be-remembered item. Following illumination of the final list item, all items disappeared. When the items reappeared for recall, they reappeared in different random locations in the horizontal row. Participants were instructed to point to each item in the order that it had been illuminated. Each child received three blocks of trials, of which the order of the first two were counterbalanced. In one block, items disappeared, then immediately reappeared for recall (i.e., "immediate recall"). In the other block, items remained off the screen for 15 seconds prior to reappearing for recall (i.e., "delayed recall"). In the final block, all children were instructed to name each item as its border illuminated (i.e., "point-and-name"). Scores were calculated as the total number of items recalled in the correct serial position across all eight lists of that block. Note that the RRR used the longest list length recalled in order to adhere to the original scoring procedures used by Flavell et al. (1966). The points-based scoring procedure was used here to capitalize on its greater sensitivity and variability (see Unsworth & Engle, 2007).

Verbalization status

As in the original methods described by Flavell et al. (1966), children who participated in the RRR project were classified as verbalizing "never," "sometimes," or "usually" based on a blind rater's observations of the child making lip movements and/or overtly labeling items at any point during the trial (i.e., list presentation; delay, if applicable; and recall). Details regarding the coding protocol, experimenter training, and interrater reliability are available in Elliott et al. (2021). Briefly, if the rater heard or could lip-read a specific item label with certainty, that trial was rated as a "1"; if the rater was reasonably certain that the child was labeling (e.g., s/he observed repetitive lip movements or sounds, but could not identify a specific item label), the trial was coded as a "2"; if the rater observed no discernible lip movement or speech indicative of labeling, the trial was coded as a "3." Children who were observed verbalizing (i.e., received "1" or "2") on at least half of the delayed or immediate recall trials (8 or more out of 16 trials) were classified as verbalizing "usually." Children who were observed verbalizing on at least 1 but fewer than 8 trials were classified as "sometimes" verbalizing. Children who were not observed verbalizing on any trials were classified as "never" verbalizing. Despite often being combined into a dichotomous "verbalized" versus "nonverbalized" variable (i.e., the "usually" or "sometimes" categories combined versus the "never" category) in both the original study and the replication project, all three categories were retained here.

Isolated naming speed

After completing both the Immediate Recall and Delayed Recall blocks, children were instructed, "Please say the name of the pictures you see," and were then shown each of the images one at a time. If the child provided the expected label, the experimenter pressed the "Y" key; if the child provided an alternative, but appropriate, label (e.g., *sail* for *flag, bird* for *owl*), the experimenter pressed "N" and was provided an open-ended response prompt in which to type the child's provided label. Response latency to the image of the apple (median = 5.3 seconds), which was the first image shown to each child, were consistently slower than the response times to the remaining six images (medians ranging from 1.8 seconds to 2.1 seconds), so responses to the apple image were excluded from all analyses. Like many response time measurements, isolated naming speed was positively skewed even after removing "apple." Because the labeling portion of the task was not designed with this analysis in mind, it is unclear which long naming times reflect actual lexical access struggles and which are due to a lack of standardization. Therefore to minimize undue influence of outliers, each child's isolated naming speed was estimated as their median response latency for the remaining six items.[2]

Statistical analyses

For each age group, a mediation analysis was used to test the hypothesis that verbalization mediates the relationship between isolated naming speed and recall. The current analyses focused primarily on performance in the immediate serial recall block because immediate recall is a common measure of short-term memory in clinical assessments.

The analyses were implemented using the *mediation* package (version 4.5.0; Tingley, Yamamoto, Hirose, Keele, & Imai, 2014) in R (R Core Team, 2021) which computes unstandardized indirect effects for 1000 bootstrapped samples to calculate the 95% confidence interval. Inferential statistics reported on the full dataset (Elliott et al., 2021) are not reiterated here, though descriptive statistics for this subset of data are reported.

Exploratory analyses were conducted to better understand the role of naming speed variability across development. Predictions regarding naming speed and delayed recall were less straightforward than for the predictions related to immediate serial recall and thus were also examined through exploratory analyses. The indirect pathway for delayed recall can be inferred after our planned analyses: the direct path from isolated naming speed to verbalization frequency would be the same for delayed recall, as reported in the mediation paths for immediate recall. Moreover, Elliott et al. (2021) observed that lenient verbalization categorization (i.e., children who "never" verbalized versus children who either "sometimes" or "usually" verbalized) predicted 5- and 6-year old's delayed recall (this was not tested in 7- and 10-year-olds). However, it was unclear a priori whether the direct paths between isolated naming speed and delayed recall would change relative to immediate recall. Rehearsal is seemingly more useful for maintaining items during a long delay. If individual differences in rehearsal mask individual differences in phonological recoding – as suggested by Hitch et al. (1989) – then relations between isolated naming speed and delayed recall should be muted, especially for older children. However, one could also argue that because rehearsal relies on phonological recoding, the increased task demands associated with delayed recall may cause even subtle individual differences in naming speed to carry more predictive value.

Results

As previously reported from the full dataset, the absolute number of children observed verbalizing increased with age (Table 1) and recall improved with age (Figure 1). Notably, though, the current analysis uses total number of items recalled in the correct serial position rather than the less sensitive longest span. Therefore, separate one-way ANOVAs with this more sensitive scoring procedure confirmed that immediate recall increased with age, $F(3, 930) = 291$, $p < .001$, $\eta_p^2 = 0.48$. All Tukey HSD post hoc comparisons were significant, $p < .001$, confirming that all groups differed from one another. Also as expected, a one-way ANOVA indicated that median isolated naming speed decreased with age, $F(3, 930) = 37.5$, $p < .001$; $\eta_p^2 = 0.11$. Tukey HSD post hoc tests controlling for multiple comparisons indicated that median isolated naming speeds differed significantly across all groups $p < .01$, with the exception of the 6- and 7-year-old groups, $p = .06$ (Figure 2).

Association of isolated naming speed and immediate recall within age groups

If the relative contribution of speeded lexical access shifts throughout development, we should observe a changing mediation pattern across our four age groups. Therefore, we report a separate mediation analysis for each age group. As predicted, the pattern of mediation changed throughout development (Figure 3a-d). For 5-year-olds, the direct effect of isolated naming speed on immediate serial recall was not significant either with (−0.24) or without (−0.50) mediation. However, the indirect effect was −0.15 * 1.65 = −0.25, with 95% CI [−0.52 to −0.08]; thus, 5-year-olds displayed a statistically significant indirect effect

Table 1. Verbalization classification by age group.

	"Never"	"Sometimes"	"Usually"	Total
5-year-olds	51 (24%)	76 (36%)	83 (40%)	210
6-year-olds	28 (12%)	81 (33%)	134 (55%)	243
7-year-olds	19 (7%)	69 (27%)	170 (66%)	258
10-year-olds	14 (6%)	37 (17%)	172 (77%)	223

The number (percentage) of children in each age group that were classified as verbalizing "never," "sometimes," or "most of the time." These values vary slightly from Elliott et al. (2021) because of missing data.

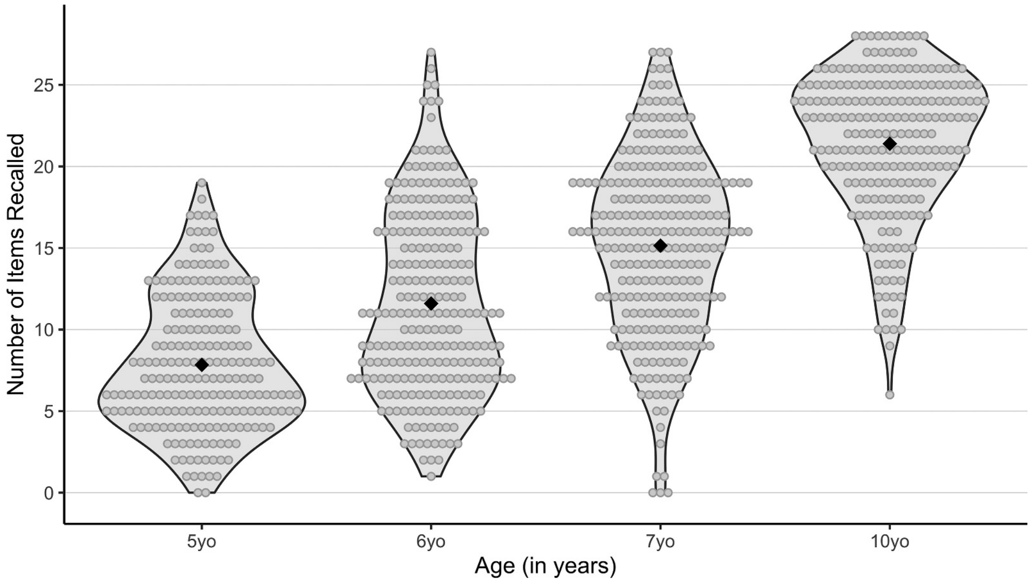

Figure 1. Violin plots of the total number of items recalled in the immediate serial recall block across all lists at each age. The maximum possible score was 28. Individual data points are indicated with gray circles. The mean for each age group is marked with a black diamond.

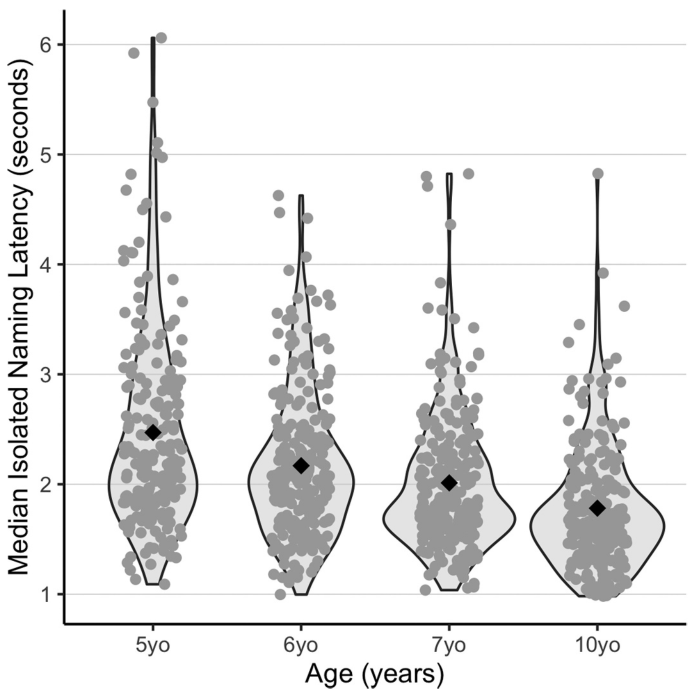

Figure 2. Violin plots of median naming speed (latency in seconds) at each age. Individual data points are indicated with gray circles. The mean for each age group is marked with a black diamond.

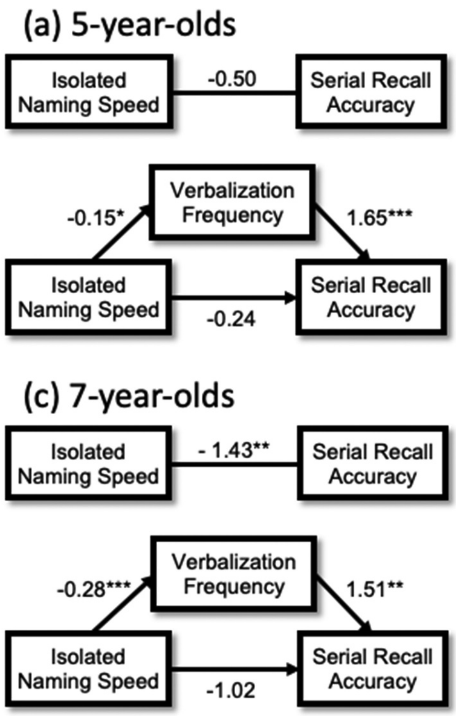

Figure 3. The effect of naming speed (latency in seconds) on immediate serial recall, with and without mediation by verbalization frequency (lower and upper figure parts, respectively). * < .05, ** <.01, *** <.001.

($p < .001$), with the regression coefficient between isolated naming speed and verbalization status ($p = .01$), and the regression coefficient between verbalization status and serial recall accuracy ($p < .001$) both significant (Figure 3a). In contrast, the 6-year-olds' isolated naming speed had direct effects (−1.66, $p = .002$) on serial recall that were partially mediated by verbalization status. The pattern changed again in the 7-year-old group; the direct effect of isolated naming speed on recall (−1.43, $p = .01$) was fully mediated by verbalization status −0.28 * 1.51 = −0.41, with 95% CI [−0.80 to −0.10] (Figure 3c). For the 10-year-olds, isolated naming speed had no effect either directly or indirectly on immediate serial recall (Figure 3d).

Exploratory analysis

The use of median naming speed necessarily smooths variability both within individual children and across age groups. To get a sense of this variability while minimizing the influence of extreme values, we divided the 5-year-old group into those whose median isolated naming speeds were comparable to the 10-year-old group (i.e., isolated naming speeds less than 3 seconds; see Figure 2), versus those whose median isolated naming speeds where slower than the 10-year-olds. By age 10, naming speed was no longer predictive of immediate serial recall. Thus, a naming speed of 3 seconds appears to provide sufficiently fast lexical access to accomplish the task given the current 2 second interstimulus interval. Of the 5-year-old children who "usually" verbalized, 88% (73 out of 83) had median isolated naming speeds of less than 3 seconds. Of the children who "sometimes" verbalized, 76% (58 out of 76) had median isolated naming speeds of less than 3 seconds. Finally, of the children who "never" verbalized, only 67% (34 out of 51) had median isolated naming speeds of less than 3 seconds. We used the same 3-second demarcation described above on each of the items from the isolated naming task. First, we indicated whether each response (excluding apple, the first item) was made in 3 seconds or less. Then, for each child across all age groups, we tallied the number of responses (out of 6) which were within that cutoff. Visual inspection of Figure 4 reveals that the proportion of children who said each of the six items within that 3-second timeframe increased with age.

The mediation analyses revealed a similar pattern for delayed recall as was present for immediate recall, though with somewhat smaller effect sizes (Figure 5a-5d). The direct paths between naming speed and delayed recall were only significant for the 6- and 7-year-olds. However, for both age groups, verbalization frequency fully mediated the effect. In contrast, the 6-year-olds continued to show a direct effect of isolated naming speed and immediate recall after verbalization status was included in the model. Notably, in addition to replicating the findings of Elliott et al. (2021) that verbalization frequency was predictive of delayed recall for 5- and 6-year-olds, the current analysis revealed a similar relationship in 7- and 10-year-olds.

Discussion

A large-scale, multilab Registered Replication Report of Flavell et al. (1966) recently revealed the extent of individual and age-related differences in spontaneous verbalizations during serial recall (Elliott et al., 2021). Although that replication did not seek to identify underlying mechanisms, anecdotal observations and the literature on reading development

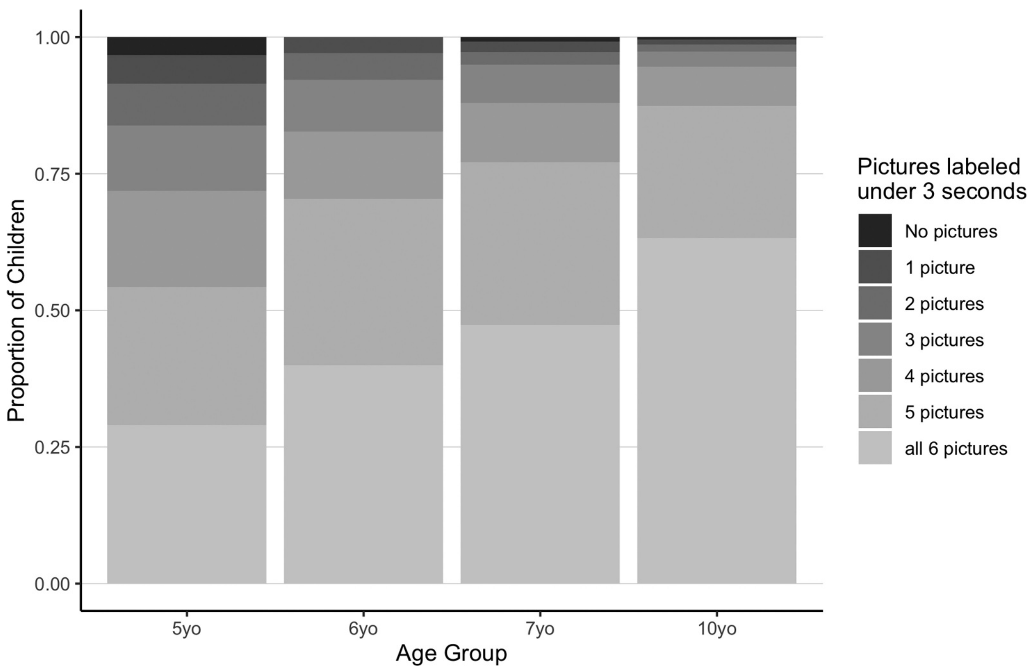

Figure 4. Stacked histogram displaying how many children in each age group labeled either 0, 1, 2, 3, 4, 5, or 6 images from the task (excluding *apple*) within 3 seconds.

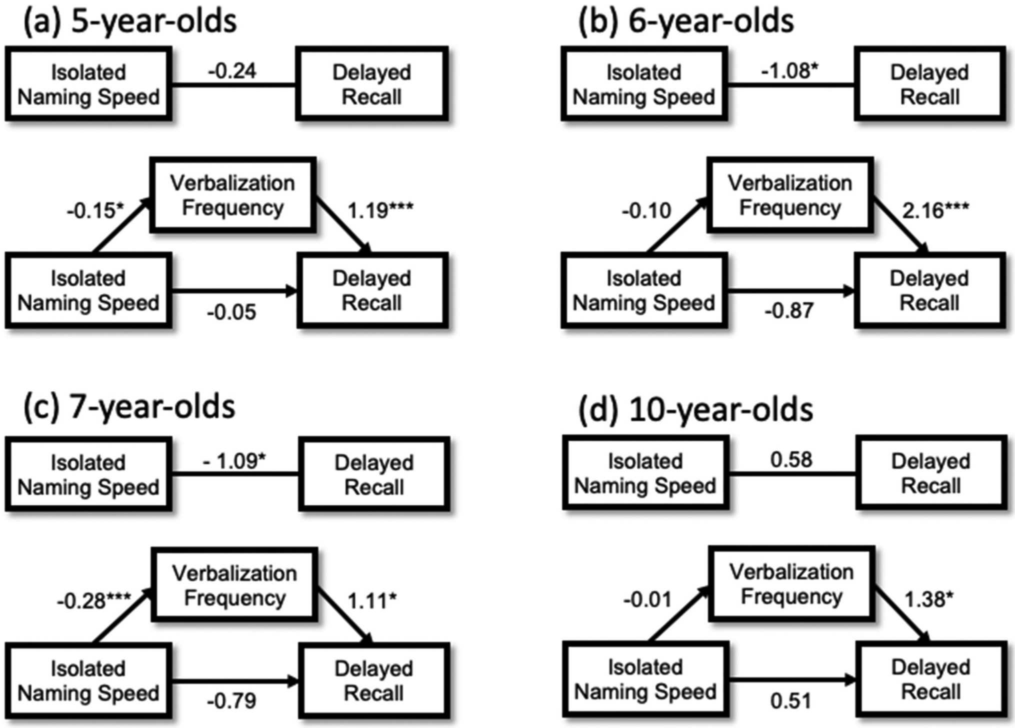

Figure 5. The effect of naming speed (latency in seconds) on delayed serial recall, with and without mediation by verbalization frequency (lower and upper figure parts, respectively). * < .05, ** <.01, *** <.001.

suggest that efficient lexical access may play a role in the ability to verbalize when instructed. Fortunately, incidentally collected data allowed us to assess whether isolated naming speed predicts both verbalization status and serial recall, as well as to postulate the developmental trajectory of phonological recoding within short-term and working memory. One impetus for conducting the replication on a large scale was to examine the generalizability (robustness versus variability) of the original findings. To this end, the replication found no effects of lab location on either recall or verbalization (Elliott et al., 2021). Therefore, rather than explicitly comparing children from different cultural or linguistic backgrounds, the current study included all children in each age group to better understand the full range of individual variability. Despite the potential contributions of culture and linguistic variability within our sample, a clear developmental pattern emerged.

As expected, isolated naming speed decreased from 5- to 10-years-of-age. As previously reported, older children were more likely to be classified as verbalizers and also had higher immediate serial recall accuracy. However, the primary question of the current study was whether isolated naming differentially predicted immediate serial recall across our age groups. This question was motivated by two observations: First, work from reading development suggests that the relative contributions of lexical access and processing speed shift during childhood for that skill. Although other studies have examined the relationships of rapid naming (AuBuchon et al., 2015) and repetition speed (Case et al., 1982) with serial recall, neither of these measures isolate lexical access from general processing skills; and studies which have directly examined isolated naming speed and memory span have only tested children who are already rehearsing. Second, Elliott et al. (2021) reported that 5-year-olds were capable of identifying each picture during a self-paced discrete naming test; yet many of these children struggled to produce labels during the point-and-name condition when presentation occurred every two seconds.

Development of phonological recoding

Our first hypothesis was that efficient lexical access is a basic, underlying mechanism that supports spontaneous use of phonological recoding when multiple items need to be encoded sequentially. The hypothesis that isolated naming speed predicts verbalization status was generally confirmed. In the planned analyses, median isolated naming speed predicted verbalization status for the 5- and 7-year-old groups but did not reach significance in the 6-year-old. Isolated naming speed had no relation to verbalization status in the 10-year-old group (Figures 3a-3d, isolated naming speed to verbalization paths).

Despite no explicit instruction to quickly produce the picture names, all but seven (out of 223) 10-year-olds' median naming speeds were less than 3 seconds, and 87% of 10-year-olds had isolated naming speeds within 3 seconds for at least 5 of the 6 pictures included here (Figures 2 and 4). Considering that the isolated naming measurements taken here also include the experimenters' button push, children whose isolated naming speed was 3 seconds or faster could likely produce item labels within the 2 second interstimulus interval used during the main serial recall tasks. Moreover, 12 of the 10-year-olds reported using internal speech strategies even though they overtly displayed no verbalization behaviors (Elliott et al., 2021). Therefore, it appears that by 10 years of age, most children's lexical access is efficient enough to support the spontaneous sequential phonological recoding of multiple items. It is possible that changing elements of the methodology (e.g. shortening/lengthening the interstimulus interval, presenting items auditorily rather than visually, or requiring spoken responses at recall) would either facilitate or further impede children's use of phonological strategies, shifting the age at which naming speed holds predictive value.

For the three younger age groups, even the seemingly simple skill of sequential phonological recoding may not yet be automatized; therefore, variability in both isolated naming and verbalization was detectable and predictive of immediate serial recall, although not directly in the case of the 5-year-olds. The primary difference in verbalization status for the 6- and 7-year-olds compared to the 10-year-olds was that more 6- and 7-year-olds were classified as "sometimes" rather than "usually" verbalizing (Table 1). The three groups of younger children also had slower median isolated naming speed (Figure 2) and more intra-child variability in isolated naming speed (Figure 4). It appears that 5-, 6- and 7-year-olds were attempting to use a phonological recoding strategy, but lexical access was slower, less efficient, less consistent, and perhaps more effortful.

Relationship between phonological recoding and short-term memory

The finding that, by 10 years of age, isolated naming no longer predicted verbalization was also consistent with our second hypothesis. If capacity, processing speed, and strategy use each have their own developmental trajectories, each might differentially predict short-term and working memory at different ages. The current study focused on the development of a phonological recoding strategy. As predicted, the strength of the direct relationship between isolated naming speed and immediate serial recall had a U-shape across development (Figures 3a-3d, top horizontal paths). Consistent with the findings of Hitch et al. (1989) who found no relation between isolated naming and span in 8- and 11-year-olds, isolated naming speed did not predict span in the 10-year-olds studied here. Isolated naming directly predicted immediate serial recall only for the 6- and 7-year-olds. However, the reason for the lack of relation is likely different for the 5-year-olds than for the 10-year-olds.

As previously described, by age 10, most children's lexical access is efficient enough to support sequential phonological recoding and thus serial recall, given the current methodology. Therefore, individual differences in recall due to phonological recoding are likely small relative to the contributions from individual differences in capacity, processing speed, or other more complex strategies. In contrast, at age 5, a substantial portion of children showed no evidence of phonological recoding during serial recall. Specifically, about one quarter of 5-year-olds were classified as "never" verbalizing. If these children made no attempt to engage in lexical retrieval during the memory tasks, their isolated naming speeds serve as noise in the direct relationship; in other words, individual differences in naming speed introduces meaningless variability for the children who are not verbalizing. Fortunately, the data from Elliott et al. (2021) identified precisely which children were observed verbalizing, and therefore allowed for a test of the indirect relationship of isolated naming on serial recall, mediated by frequency of verbalization.

Development of phonological recoding as a support for short-term memory

Phonological recoding, as an often covert skill, may be hard to identify in a clinical setting; consequently, isolated naming and age could be two useful pieces of information a clinician has to identify the underlying source of a child's poor serial recall. However, to put these data points in context, we need to understand changes in the full model across development. For example, the results discussed below may suggest that a 6- or 7-year-old who has relatively poor immediate serial recall and slow naming speeds may not be utilizing phonological recoding to support memory; thus, drills that improve rapid labeling and lexical access may also improve short-term memory performance. In contrast, a child of the same age with poor serial recall but fast isolated naming speeds may have attentional or processing concerns (e.g. ADHD) which instead underlie their memory problems.

We only made strong predictions for the 5-year-olds regarding the mediated model. In line with this prediction, the indirect relationship between isolated naming speed and recall – through verbalization frequency – was significant. The children with faster isolated naming speeds were more likely to be classified as verbalizers and had higher memory spans as well. Notably, no indirect relationship was observed in the 10-year-olds, further strengthening the conclusion that the absence of a direct relationship early in the development of phonological recoding occurs for a different underlying reason than the lack of a relationship once this skill is developed.

The developmental changes between 6 years 1 month and 7 years 11 months – as captured in our 6- and 7-year-old groups – are less clear. For 6-year-olds, verbalization frequency accounted for only a portion of the relationship between isolated naming speed and immediate recall. In contrast, verbalization frequency fully mediated the relationship between isolated naming and recall in the 7-year-old group (Figures 3a-3d). A possible explanation is that this age range represents the period of development in which most children are spontaneously attempting phonological recoding in a short-term memory task, but still vary in the efficiency with which they can carry out this task. Although recall increased from 6 to 7 years (Figure 1), median naming speed was similar for these two groups (Figure 2). Both groups also had a large subset of children who failed to consistently provide fast labels (Figure 4). Despite both age groups having a subset of children struggling to quickly label items, we might also expect some children (especially in the 7-old-group) to be able to label items well within the two-second interstimulus interval used here (Figure 2). These children could then use the phonological codes in service of rehearsal which would further increase span. The results of Flavell et al. (1966) are often interpreted as support that 7-year-olds engage in rehearsal. However, it is worth noting that Flavell et al.'s coding of verbalization frequency, and thus Elliott et al.'s (2021) coding, did not differentiate either partial or cumulative rehearsal from simple phonological recoding. A child who only labeled images during encoding or retrieval was given the same classification as a child who additionally rehearsed items during a delay period – be it extra time during the interstimulus interval or the delay period of the delayed recall block. In fact, both Flavell and colleagues (anecdotally) and Elliott and colleagues (statistically based) noted that during the delayed recall trials, verbalization behaviors were more prevalent during both the encoding period and the recall period than during the delay period. A more nuanced examination of these verbalization data is necessary to understand the transition from phonological recoding to rehearsal during this point in development.

Most surprising, perhaps, were the changes observed from 7 to 10 years of age. Neither Flavell et al. (1966) nor Elliott et al. (2021) showed strong evidence for an increase in verbalization from 7 to 10 years of age. Nonetheless, the 10-year-olds had higher recall, whether scored as longest list length (Elliott et al.) or by the total number of items correct as scored in the current analysis. Taken together, the data presented here illustrate that, although most 7-year-olds spontaneously verbalize, these children still vary in their lexical access speed. Individual differences in lexical access would affect the efficiency of phonological recoding and likely have downstream effects on rehearsal. Rehearsal itself is also likely to vary in efficiency from 7 to 10 years of age. Although average speech duration decreases dramatically until age 7, it continues to decrease even through the teenage years (Smith & Zelaznik, 2004). Further, even when children show average articulation durations comparable to adults, productions of individual tokens from a given child have more variable durations than tokens produced by adults (Smith, 1991). Speech motor movements remain quite variable in 7-year-old children, suggesting that the creation and execution of the speech motor plan has not reached adult-like efficiency (Smith & Zelaznik, 2004).

The exploratory mediation analysis for delayed serial recall may shed light on the development of verbalization from age 7 to age 10. Notably, the direct path between naming speed and recall remained insignificant for 5- and 10-year-olds (and became slightly weaker for the 6- and 7-year-olds) in delayed relative to immediate recall (Figure 5). That the general pattern persisted even when the delay necessitated additional maintenance strategies, such as rehearsal, might suggest that isolated naming speed alternatively reflects a knowledge component that is important for recall, but independent of verbalization. However, the stronger claim made here is that the knowledge component is specifically lexical knowledge which can support phonological recoding and, in turn, rehearsal. This claim is also consistent with the path between verbalization and recall which became weaker for 6- and 7-year-olds relative to immediate serial recall, but stronger for 10-year-olds relative to their immediate serial recall. This pattern might result from the waning usefulness of phonological recoding to the younger groups if rehearsal is not being used to reactivate the phonological representation over the delay.

Conclusions

The current study reanalyzed data from Elliott et al.'s (2021) multilab Registered Replication Report of Flavell et al. (1966) to better understand the foundational mechanisms for phonological recoding and rehearsal in short-term memory during development. Isolated naming speed directly predicted immediate serial recall at ages 6 and 7 years, though this relationship was mediated by verbalization – partially at age 6 and fully at age 7. However, isolated naming only predicted serial recall indirectly (via verbalization) at age 5. By age 10, isolated naming no longer had predictive value, either directly or indirectly. These findings imply that fast lexical access is a precursor to successful, spontaneous phonological recoding of a series of items. Once children begin to spontaneously use phonological recoding in service of short-term and working memory, lexical access and speech-motor processes continue to become more consistently efficient, further benefiting recall, until automaticity is reached. These findings help describe a model of rehearsal development. Specifically, development of phonological recoding and rehearsal strategies should not be viewed as an all-or-none phenomenon; nor should the relations between timing of speech output processes (as a proxy for efficiency) and recall be evaluated uniformly across age groups. Instead, there is an interplay of strategy engagement, efficiency, and task demands that changes throughout development.

Notes

1. The original 17 participating laboratories reported testing 1,038 children. The protocol of the primary study specified that a child should be excluded if the child could not adequately label a picture from the set. These decisions were made by each lab group, and exclusions were made prior to data aggregation. Labs reported only 61 children (or 6%) of tested children were excluded based on this criterion, resulting in 977 children in the final RRR sample.
2. In keeping with convention for clinical "naming speed" (often rapid naming) tasks, response latency was retained as the dependent measure rather than transforming to a rate (i.e. items/second) as would be expected for a value of speed. However, this inverse transformation was made in order to assess reliability across the remaining six pictures, $\alpha = 0.761$ [0.65, 0.86].

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Data availability statement

The data described in this article are openly available in the Open Science Framework at https://osf.io/3yba9/?view_only=63c52f8fdd6240be80b79b77efff54a5.

Open scholarship

This article has earned the Center for Open Science badges for Open Data and Open Materials through Open Practices Disclosure. The data and materials are openly accessible at https://osf.io/3yba9/?view_only=63c52f8fdd6240be80b79b77efff54a5.

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