1   oREV: an Item Response Theory based open receptive vocabulary task for 3 to 8-year-old

2   children

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Abstract

Individual differences in early language abilities are an important predictor of later life outcomes. High-quality, easy-access measures of language abilities are rare, especially in the preschool years. The present study describes the construction of a new receptive vocabulary task for children between 3 and 8 years of age. The task was implemented as a browser-based web application, allowing for in-person as well as remote data collection via the internet. Based on data from N = 581 German-speaking children, we estimated the psychometric properties of each item in a larger initial item pool via Item Response Modeling. We then applied an automated item selection procedure to select an optimal subset of items based on item difficulty and discrimination. The so-constructed task has 20 items and correlates with the full task (52 items) at a rate of .97. The construction, implementation and item selection process we described here makes it easy to extend the task or adapt it to different languages. All materials and code are freely accessible to interested researchers. The tasked can be used via the following website: https://ccp-odc.eva.mpg.de/orev-demo/.

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oREV: an Item Response Theory based open receptive vocabulary task for 3 to 8-year-old children

Introduction

Individual differences in language abilities are early emerging, stable across development, and predictive of a wide range of psychological outcome variables including cognitive abilities, academic achievement, or mental health (Bornstein, Hahn, Putnick, & Pearson, 2018; Marchman & Fernald, 2008; Morgan, Farkas, Hillemeier, Hammer, & Maczuga, 2015; Schoon, Parsons, Rush, & Law, 2010; Walker, Greenwood, Hart, & Carta, 1994). From a methodological perspective, high-quality, easy-access measures of language abilities are therefore central to both basic and applied research on individual differences in language abilities. Ideally, such measures should also be comparable across languages in order to study which developmental processes are language-specific and which are shared more widely. Developing such measures is very time and resource intensive and, as a consequence, few exist. In this paper, we describe the construction of a new receptive vocabulary task for German-speaking children. Its psychometric grounding in Item Response Theory makes the measure robust and efficient. Its web-based design and implementation makes the measure easy to adapt and administer in different settings (in-person or remote) and thereby facilitates the scaling of data collection.

Language has many facets and aspects that can be focused on when assessing individual differences between children. One particular productive approach has been the study of children's vocabulary skills, that is, their knowledge of word-object mappings. This skill can be most effectively assessed, for example by asking children to name an object (production) or pick out an object that matches a word they just heard (comprehension). Children with larger vocabularies are taken to have advanced language skills more broadly. This assumption seems to be justified in light of strong correlations between vocabulary size and other language measures such as grammatical (Hoff, Quinn, & Giguere, 2018; e.g.,

⁶¹ Moyle, Weismer, Evans, & Lindstrom, 2007) or narrative skills (Bohnacker, Lindgren, &

⁶² Öztekin, 2021; Fiani, Henry, & Prévost, 2021; Lindgren & Bohnacker, 2022; Tsimpli,

⁶³ Peristeri, & Andreou, 2016). Vocabulary skills have also been used as an indicator of

⁶⁴ developmental language disorders more broadly (Spaulding, Hosmer, & Schechtman, 2013).

⁶⁵ Finally, many of the predictive relations found for early language skills mentioned above

⁶⁶ are based on vocabulary measures (Bleses, Makransky, Dale, Højen, & Ari, 2016; Roberta

⁶⁷ Michnick Golinkoff, Hoff, Rowe, Tamis-LeMonda, & Hirsh-Pasek, 2019; Pace, Alper,

⁶⁸ Burchinal, Golinkoff, & Hirsh-Pasek, 2019; Pace, Luo, Hirsh-Pasek, & Golinkoff, 2017).

⁶⁹ This set of findings underlines the importance of high-quality vocabulary measures.

⁷⁰ A range of measures exist to assess vocabulary skills in children. For very young

⁷¹ children (up to 3 years), a very popular instrument is the MacArthur–Bates Communicative

⁷² Development Inventories (CDIs) (Fenson et al., 2007). Parents are provided with a list of

⁷³ words and are asked to check those the child understands and/or produces. The CDI exists

⁷⁴ in different forms (e.g., Makransky, Dale, Havmose, & Bleses, 2016; Mayor & Mani, 2019),

⁷⁵ including an online version (DeMayo et al., 2021), and has been adapted to many different

⁷⁶ languages (see Frank, Braginsky, Yurovsky, & Marchman, 2021). Thanks to concentrated

⁷⁷ collaborative efforts, data from thousands of children learning dozens of languages has been

⁷⁸ pooled in centralized repositories (Frank, Braginsky, Yurovsky, & Marchman, 2017;

⁷⁹ Jørgensen, Dale, Bleses, & Fenson, 2010). As such the CDI provides positive example for a

⁸⁰ high-quality, easy-access measure that is heavily used in both basic and applied research.

⁸¹ However, the CDI best suited for children in the first two years of life. From 2 years

⁸² onward, children are usually tested directly. Vocabulary assessment is often part of

⁸³ standardized tests of cognitive abilities (Bayley, 2006; Gershon et al., 2013; e.g. Wechsler &

⁸⁴ Kodama, 1949). In addition, a range of dedicated forms exist for English (e.g., Dunn &

⁸⁵ Dunn, 1965; Dunn, Dunn, Whetton, & Burley, 1997; Roberta M. Golinkoff et al., 2017),

⁸⁶ German (Glück & Glück, 2011; Kauschke & Siegmüller, 2002; Kiese-Himmel, 2005;

⁸⁷ Lenhard, Lenhard, Segerer, & Suggate, 2015) and other languages.

88   Yet, from the perspective of a researcher, these existing measures are often

89 problematic for several reasons. Because they are standardized and normed instruments

90 using them ensues substantial licensing costs. For the same reasons, the corresponding

91 materials are not openly available which makes it difficult to expand or adapt them to

92 different languages. Most measures also rely on in-person, paper-pencil testing which

93 makes large-scale data collection inefficient and extremely costly. Whenever more portable,

94 computerized versions exist, they come with additional costs. As a consequence, nothing

95 comparable to the collaborative research infrastructure built around the CDI exists for

96 vocabulary measures for older children.

97   The development of so-called Cross-linguistic Lexical Tasks (CLTs; Haman,

98 Łuniewska, and Pomiechowska (2015)) constitutes a promising framework that might help

99 to overcome these issues. CLTs are simple picture-choice and picture-naming tasks aimed

100 at assessing comprehension and production of nouns and verbs. In a collaborative effort

101 involving more than 25 institutions, versions for dozens of different languages have been

102 developed following the same guiding principles (Armon-Lotem, Jong, & Meir, 2015;

103 Haman et al., 2017, 2015). In addition to cross-linguistic studies with mono-lingual

104 children, this procedure makes CLTs ideally suited to assess multi-lingual children. The

105 tasks and the materials are not commercially licensed and can thus be freely used for

106 research purposes.

107   Despite these many positive characteristics, CLTs are limited in two important ways.

108 Despite these many positive characteristics, CLTs are limited in two important ways. First,

109 they were designed for children between 3 and 5 years and consequently they show ceiling

110 effects for older children in this age range (Haman et al., 2017). This greatly limits their

111 usefulness in research across the preschool years. Second, and maybe more important,

112 CLTs have been developed following clear linguistic guidelines – but *without* a strict

psychometric framework[1]. As a consequence, it is unclear how the different items relate to the underlying construct (e.g., vocabulary skills). We do not know which items discriminate between different levels of skill and are therefore particularly diagnostic e.g., at different ages. Items could also be biased and show differential measurement properties in relevant subgroups (e.g. girls and boys). In addition, some items might be simply redundant in that they measure the underlying construct in the same way. Such characteristics could make the task unnecessarily long. Modern psychometric approaches like Item Response Theory (IRT) (Kubinger, 2006; Lord, 2012) assess the relation between each individual item and the underlying – latent – construct one seeks to measure. This focus allows for evaluating the quality and usefulness of each item and thereby provides a solid psychometric basis for constructing efficient and high-quality tasks. In combination with a computerized implementation, IRT allows for adaptive testing during which participants are selectively presented with highly informative items given their (constantly updated) estimated level of ability. However, IRT-based task construction requires a higher initial investment: it takes a large item pool and large sample sizes to estimate the item parameters that guide the selection of the best items.

The current study

Our goal was to develop a new, high-quality, easy-access measure of receptive vocabulary skills for German-speaking children between 3 and 8 years of age. For that, we built on the existing CLT but substantially expanded the item pool. We implemented the task as a browser-based web application, which made it highly portable and allowed us to test a large sample of children online. Next, we used IRT to estimate measurement characteristics of each item in the pool. We then developed an algorithm that used these characteristics to automatically select a smaller subset of items for the final task. The implementation infrastructure and construction process we describe here make the task

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[1] The same applies to most other vocabulary measures used in developmental research.

138 easy to share with interested researchers and also provide clear guidance for how to further

139 adapt to different languages.

Item-pool generation

141   The initial item pool consisted of 32 items taken with permission from the German

142 CLT (Haman et al., 2017, 2015) and 20 new items. The addition of new items was

143 necessary due to ceiling effects for monolingual 5-year-olds in the previous version. New

144 items were generated in line with the construction of the original CLT in a stepwise process.

145 Each item consists of a target word and three distractors. To select target words, we first

146 compiled a list of age-of-acquisition ratings for 3,928 German words from various sources

147 (Birchenough, Davies, & Connelly, 2017; Łuniewska et al., 2019; Schröder, Gemballa,

148 Ruppin, & Wartenburger, 2012). From this list, we selected 20 words based on the following

149 criteria: words should refer to concepts that could easily and unambiguously be depicted in

150 a drawing, age-of-acquisition ratings should be spread equally between six and ten years of

151 age. We also computed complexity indices for each word (see Haman et al., 2017). This

152 metric, however, did not reflect a dimension that was relevant for item selection.

153   The so-selected 20 words served as additional target words in the item pool (total of

154 52 items). For each target word, we selected three distractors. The first distractor was

155 unrelated to the target word but was chosen to have a comparable rated age-of-acquisition.

156 The second distractor was semantically related to the target word (e.g. ruin – fortress; elk –

157 mammoth). The third distractor was phonetically similar to the target, that is, for

158 example, initial part was substituted, and the rest of the word was kept similar (e.g. Gazelle

159 [eng.: gazelle] – Libelle [eng.: dragonfly]). The full list of targets and distractors can be

160 found in the associate online repository. Finally, an artist (same as for the original CLT

161 items) drew pictures representing all target and distractor words. This procedure ensured

162 that the original CLT and the newly generated items formed a homogeneous item pool.

¹⁶³ **Task design and implementation**

¹⁶⁴ The task was programmed in `JavaScript` and `HTML` and presented as a website which

¹⁶⁵ could be opened in any modern web browser. In addition to participants' responses, we

¹⁶⁶ recorded webcam videos[2]. Both files were sent to a server after the study was finished. The

¹⁶⁷ task started with several instruction pages that explained to parents the task and how they

¹⁶⁸ should assist their child if needed. The task (after item selection) can be accessed via the

¹⁶⁹ following link: https://ccp-odc.eva.mpg.de/orev-demo/.

¹⁷⁰ On each trial (see Figure 1), participants saw four pictures and heard a verbal prompt

¹⁷¹ (pre-recorded by a native German speaker) asking them to select one of the pictures

¹⁷² (prompt: "Zeige mir [target word]"; eng.: "Show me [target word]"). The verbal prompt

¹⁷³ was automatically played in the beginning of the trial but could also be replayed by clicking

¹⁷⁴ on a loudspeaker button. Selected pictures were marked via a blue frame. Participants

¹⁷⁵ moved on to the next trial by clicking on a button at the bottom of the screen. If children

¹⁷⁶ could not select the pictures themselves (via mouse click or tapping on the touch screen),

¹⁷⁷ they were instructed to point to the screen and parents should select the pointed-to picture.

¹⁷⁸ The positioning of the pictures (target and distractors) was counterbalanced so that

¹⁷⁹ the target picture appeared equally often in each corner and no more than twice in the

¹⁸⁰ same corner. We generated two versions of the task with different item orders. Each order

¹⁸¹ was created so that trial number and age-of-acquisition ratings were correlated with $r =$

¹⁸² .85. This would make later trials more difficult, but not perfectly so.

¹⁸³ **Item selection**

¹⁸⁴ The goal of the item selection process was to find the minimal subset of items

¹⁸⁵ necessary to measure vocabulary skills on an individual level. As a first step, we collected

¹⁸⁶ data for the full 52-item task from a large sample of children in the target age range. Next,

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[2] Due to access rights issues, webcam recording was not possible when participants used iOS devices.
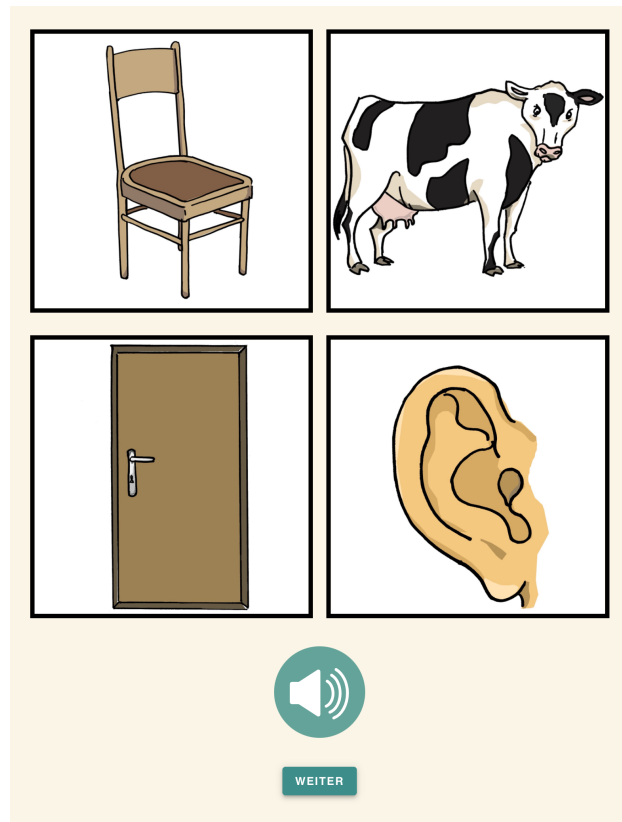
Figure 1. Screenshot from the task. On each trial, participants heard a word and were asked to pick out the corresponding picture. Verbal prompts could be replayed by pressing the loudspeaker button.

187   we determined which IRT model best fit the data and used this model to estimate the item

188   parameters (difficulty and discrimination). We removed items that showed differential item

189   functioning (DIF) when the data was split either by sex or by trial order. Finally, we used

190   a simulated annealing process (Kirkpatrick, Gelatt Jr, & Vecchi, 1983) to determine the

191   size of the reduced task and to select the best items. Data collection was pre-registered at

192   https://osf.io/qzstk. The pre-registered sample size was based on recommendations found

193   in the literature (Morizot, Ainsworth, & Reise, 2007). The datasets generated during the

194   current study as well as the analysis code are available in the following repository:

195   https://github.com/ccp-eva/vocab.

Participants

Participants were recruited via a database of children living in Leipzig, Germany whose parents volunteered to participate studies on child development and who additionally indicated interest in participating in online studies. Parents received and email with a short study description and a personalized link. After one week, parents received a reminder if they had not already taken part in the study. Response rate to invitations was ~50%. The final sample included a total of 581 children (n = 307 girls) with a mean age of 5.63 (range: 3.01 – 7.99). Participants were randomly assigned to one of the two task versions. Data was collected between February and May 2022.
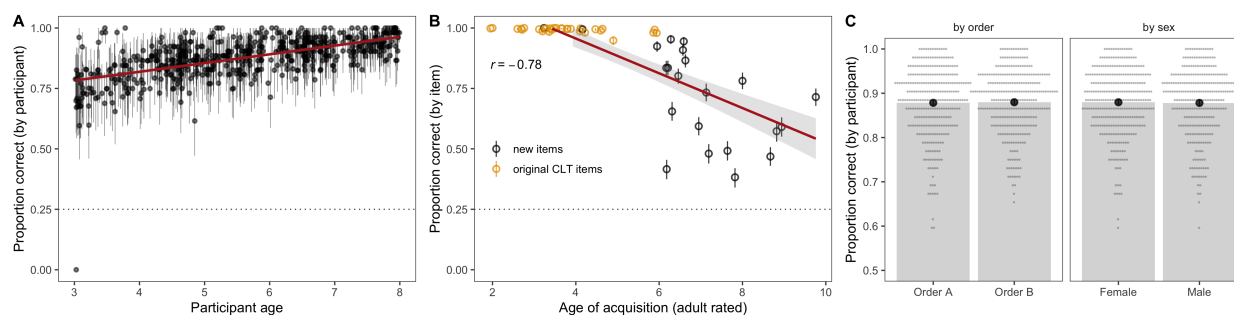
Descriptive results

Figure 2. Descriptive results of the task. A: Proportion of correct responses (with 95% CI) for each participant by age. B: Proportion of correct responses (with 95% CI) for each item by rated age-of-acquisition of the target word. C: Proportion of correct responses (with 95% CI) by trial order (left) and sex (right).

On a participant level, performance in the full task (52 items) steadily increased with age (Figure 2A). On an item level, performance was above chance (25%) for all items. Furthermore, the average proportion of correct responses was negatively correlated with age-of-acquisition ratings (Figure 2B). Figure 2B also shows the ceiling effect for the original CLT items found in Haman et al. (2017). These descriptive results replicate

Table 1

Model comparison (model parametrization)

Model	ELPD	SE(ELPD)	ΔELPD	SE(ΔELPD)
3PL	-6,089.51	80.89	0.00	0.00
2PL	-6,124.12	81.01	-34.61	8.60
1PL (Rasch)	-6,233.70	82.13	-144.19	18.20

Note. ELPD = expected log posterior density, SE = standard error, ELPD differences are in comparison to the 3PL model. Less negative ELPD values indicate better model fit.

well-known results in the literature and emphasize the added value of the newly developed items. Figure 2C shows that there were – on average – no differences between participants who received order A and order B as well as between female and male participants. This result suggests that these grouping variables are suitable to investigate differential item functioning (see below).

Item response modelling

IRT models were implemented in a Bayesian framework in `R` using the `brms` package (Bürkner, 2017, 2019). Given the binary outcome of the data, we used logistic models to predict the probability of a correct answer based on participant's latent ability and item characteristics (difficulty and discrimination). All models had converging chains and provided a good fit to the data. For details about prior and MCMC settings, please see the analysis script in the associated online repository. We compared models using Bayesian approximate leave-one-out cross-validation (Vehtari, Gelman, & Gabry, 2017) based on differences in expected log posterior density (ELPD) and the associated standard error (SE).

Table 2

Model comparison (differential item functioning)

Model	ELPD	SE(ELPD)	ΔELPD	SE(ΔELPD)
3PL split by sex	-6,065.58	80.94	0.00	0.00
3PL	-6,089.51	80.89	-23.93	8.38
3PL split by order	-6,090.34	80.75	-24.75	9.27

Note. ELPD = expected log posterior density, SE = standard error, ELPD differences are in comparison to the 3PL model. Less negative ELPD values indicate better model fit.

²²⁶   As a first step, we compared three models with increasing complexity: a 1PL (Rasch)

²²⁷ model which assumed that items only differ in difficulty but have the same discrimination

²²⁸ parameter (1), a 2PL model which additionally allows items to have different

²²⁹ discrimination parameters, and a 3Pl model which further adds a guessing parameter of

²³⁰ 0.25. Table 1 shows that the 3PL model provided – by far – the best fit. For the following

²³¹ item selection procedure, we therefore used the item parameters (difficulty and

²³² discrimination) estimated by the 3PL model.

Differential item functioning

²³⁴   As a first step in the item selection process, we removed items that showed

²³⁵ differential item functioning (DIF). DIF refers to situations in which items show differential

²³⁶ characteristics for subgroups that have otherwise the same overall score (Holland &

²³⁷ Wainer, 2012). To assess DIF for the present task, we followed the procedure suggested by

²³⁸ Bürkner (2019) and fit two extended 3PL models (one for trial order and one for sex)

²³⁹ which estimated separate item characteristics for each subgroup. As an overall assessment

²⁴⁰ of DIF we compared these extended models to the basic 3PL. We found no indication for

241 DIF based on trial order but did so for sex (see Table 2). To decide which items to remove,

242 we computed the difference between mean estimates for male and female participants for

243 each item and excluded those items for which the absolute difference was larger than two

244 standard deviations of all differences. Four items had to be excluded based on this
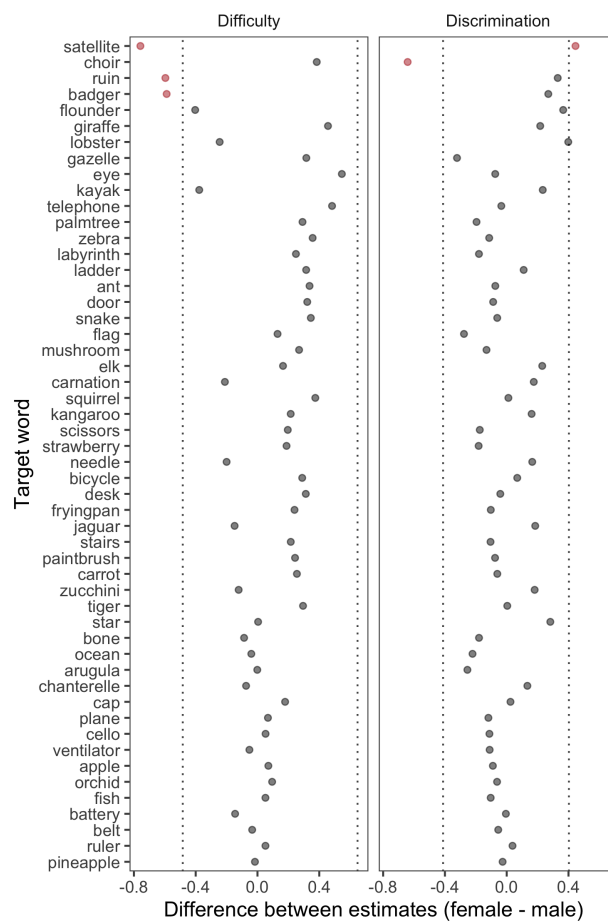
245 procedure (see Figure 3).

Figure 3. Differential item functioning. Difference between estimates for female and male participants for the two item parameters. Dashed lines show cut-off points. Red points indicate items that were excluded.

Automated item selection

The goal of this last step of the item selection process was to select a smaller subset of items that nevertheless allow for precise measurement. The basis for this selection process was an objective function which we defined to capture three important characteristics that the items of any subset should have. First, items should be equally spaced across the latent ability space. This characteristic ensures that the task is suited for different ability levels and thus for a broader range of ages. We quantified the spread of any given subset as the standard deviation of the distance (in difficulty estimates) between adjacent items. Lower values indicate smaller distances and thus an overall more equal spacing. Second, items should have maximum discrimination. That is, we preferred items that distinguished well between narrowly defined regions of the latent ability. Discrimination parameters were divided by 2 to put them on a scale comparable to the standard deviations of the distances. Third, difficulty estimates should have narrow credible intervals. The idea behind this characteristic was that many of the easier items had very wide credible intervals because most of the participants answered correctly. Of those items we sought to select the ones with more precise difficulty estimates. For scaling purposes, the width of the credible interval was divided by 6.

We used simulated annealing (Kirkpatrick et al., 1983) to find the optimal items for any given size of the subset. This process randomly explores the large space of possible subsets, beginning from a randomly selected initial subset and then successively proposing small random changes by exchanging some items which are in the subset under consideration with others outside it. If such a change increases the value of the objective function, the proposal is accepted and the improved subset is taken as the new starting point for subsequent proposals. However, to avoid the process getting trapped in local optima, proposals which decrease the value of the objective function may also be accepted, but probabilistically. The probability that a proposal which decreases the objective

272 function is accepted depends upon a parameter called "temperature", which is gradually

273 reduced from a high initial value to a lower value over the course of the simulation. During

274 the "hot" early phase, the process explores the space relatively freely, accepting decreasing

275 proposals often enough to allow it to move between local optima separated by less well

276 performing subsets, facilitating the discovery of global optima. In the later "cool" phases,

277 the process slowly converges to a strict "hill climbing" search which accepts only increasing

278 proposals, resulting in careful fine tuning of the best subset discovered in the hot phase.

279   We applied simulated annealing to subsets ranging from 5 to 40 items. For each

280 (optimal) subset we then computed the correlation between performance based on the

281 subset and based on the full task This allowed us to assess how well the subset was able to

282 capture variation between individuals in comparison to the full task. Figure 4A shows how

283 the correlation between subset and full task increase with an increasing number of items in

284 the subset. The resulting curve leveled-off at around 20 items in that adding additional

285 items to the subset did not increase the correlation any further. We therefore concluded

286 that 20 items would be the ideal size of the subset.

287   When running the simulated annealing procedure for 20 items 100 times, it always

288 returned the same item selection. We therefore chose this subset of items for the reduced

289 task. Figure 4B shows the item parameters for the selected items and Figure 4C shows

290 their item characteristic curves.

Discussion

292   Individual differences in language abilities in childhood are an important predictor of

293 later life outcomes. Yet, high-quality, easy access measures are rare, especially for pre- and

294 primary-school-aged children. Here we reported the construction of a new receptive

295 vocabulary task for German-speaking children between 3 and 8 years-of-age. Building on

296 earlier work (Haman et al., 2017), we first generated a larger initial pool with 52 items.
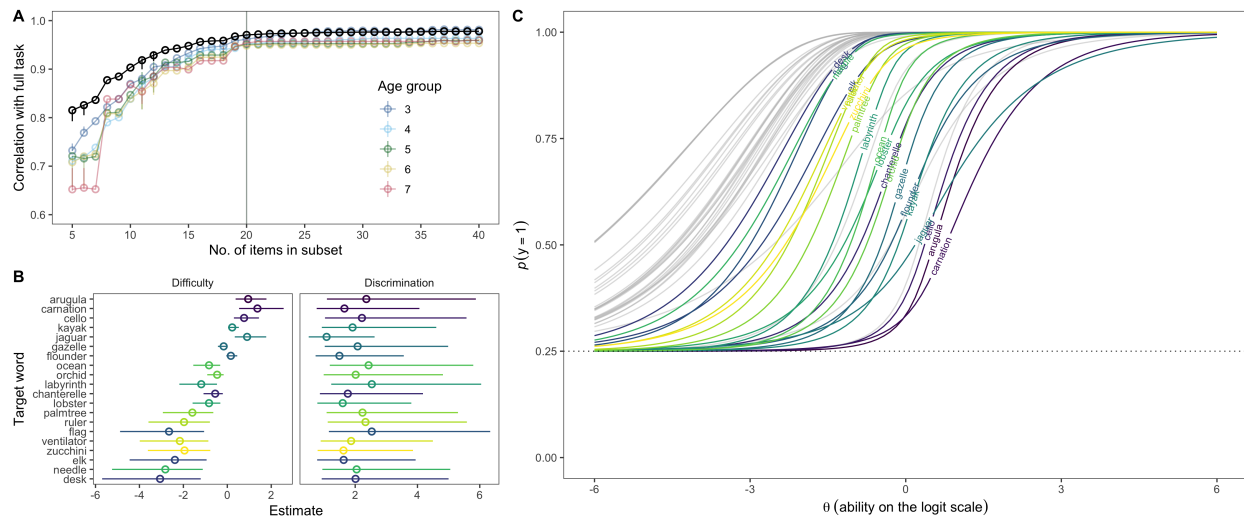
Figure 4. Item selection process. A) Correlation between reduced and full task (52 items). Points show mean correlation based on 100 iterations. Vertical lines show the range of correlations in cases when they differed between iterations. Black lines and points show correlations for the full sample and colored points and lines show correlations by age group. B) Item parameters for the selected 20 items estimated based on the 3PL model. C) Item characteristic curves for all 52 items, with excluded items in grey and selected items in color.

Next, we implemented the picture-selection task as a web application and collected data from over 500 children online. We used IRT models and an automated item selection algorithm to select a minimal set of high quality items. The so-constructed task has 20 items and correlates with the full task at a rate of .97. Its browser-based implementation makes the task highly portable and facilitates large scale data collection. The construction and item selection process we described here makes it easy to add additional items or adapt the task to different languages while retaining a high psychometric quality of the end product. The task is freely accessible to all interested researchers.

The task fills an important gap in the methods repertoire of developmental researchers studying monolingual and bilingual language development in early childhood. Existing measures show ceiling effects, come with high licensing costs and/or are not

308   available in an electronic format. Our task captures variation between children up until 8

309   years of age, is free to use and can be run on any modern web browser. However, the newly

310   constructed task with 20 items is still relatively easy, that is, most 7 year-old children will

311   solve the majority of items (87% correct responses in the present sample). As a

312   consequence, it does not distinguish well between children with very strong vocabulary

313   skills. Future extensions of the task could thus focus on adding more difficult items. Figure

314   2B (see also Brysbaert & Biemiller, 2017) shows that target word age-of-acquisition ratings

315   are a fairly good predictor of item difficulty and could be used as a basis to generate new

316   items. Extensions should focus on target words with rated age-of-acquisition above 10.

317   Further extension could other parts of speech, such as verbs and adjectives.

318   The automated item selection process we implemented critically leveraged the

319   strengths of IRT modelling. For each item in the pool we estimated its difficulty and

320   discrimination. We defined the object function we optimized via the simulated annealing

321   process so that it would yield a subset in which items would a) be equally spread out

322   across the latent ability so that the task measured equally well at different skill levels and

323   b) have maximal discrimination so that the items differentiate well between individuals

324   having similar skill levels. In addition, we prioritized items with more precise difficulty

325   estimates (i.e. narrower CrIs).

326   This procedure presents a principled way of constructing a task with good

327   psychometric properties which can easily be applied to any new set of items or versions of

328   the task in different languages. However, this approach does not make the careful,

329   principle-based construction of the initial item pool superfluous; it only selects the best of

330   the available items. Linguistic and psychometric considerations thus need to go hand in

331   hand during task construction. For example, while nouns are more similar across

332   languages, verbs are more language-specific and might have different representations or

333   even be absent as a single word, e.g. verb "wandern" (German for hiking) can be expressed

334   only by an analytical construction in Slavic languages. Furthermore, bilingual and

monolingual lexicons might vary and background factors, such as age, length of exposure or the onset of second language acquisition should be considered. Finally, morphosyntactic properties of verb grammar, such as perfective or imperfective aspect, should be considered.

A major advantage of the task presented here is its portability. Its implementation as a web application makes it easy to administer both in-person and online and also reduces the likelihood of experimenter error. In fact, we were able to collect data from more than 500 children online in just two months. It is also easy to add new items or to adapt the existing task to a new language. Of course, extensions and new adaptations require a renewed item evaluation and selection process. Nevertheless, the infrastructure and materials developed here provide a good starting point for such an endeavor. The computerized implementation of the task also allows for adaptive testing. That is, instead of all participants completing the same set of items, each participant could be presented with – potentially fewer – maximally informative items given their (continuously updated) estimated skill level. However, this would require a more elaborate back-end – capable of doing on-line parameter estimation – compared to the current version of the task.

Conclusion

We have described the construction of a new receptive vocabulary measure for German-speaking children between 3 and 8 years-of-age. The datastes and the analysis code for item selection are freely available in the associated online repository (https://github.com/ccp-eva/vocab). An online version of the task is available at the following website: https://ccp-odc.eva.mpg.de/orev-demo/. The implementation architecture (`JavaScript` and `HTML` code) and the materials can be accessed in the following repository: https://github.com/ccp-eva/orev-demo. These resources allow interested researchers to use, extend and adapt the task.

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