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Research Article

Articulating Novel Words: Children's Oromotor Skills Predict Nonword Repetition Abilities

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Purpose: Pronouncing a novel word for the first time requires the transformation of a newly encoded speech signal into a series of coordinated, exquisitely timed oromotor movements. Individual differences in children's ability to repeat novel nonwords are associated with vocabulary development and later literacy. Nonword repetition (NWR) is often used to test clinical populations. While phonological/auditory memory contributions to learning and pronouncing nonwords have been extensively studied, much less is known about the contribution of children's oromotor skills to this process.
Method: Two independent cohorts of children (7–13 years [N = 40] and 6.9–7.7 years [N = 37]) were tested on a battery of linguistic and nonlinguistic tests, including NWR and oromotor tasks.
Results: In both cohorts, individual differences in oromotor control were a significant contributor to NWR abilities; moreover, in an omnibus analysis including experimental and standardized tasks, oromotor control predicted the most unique variance in NWR.
Conclusion: Results indicate that nonlinguistic oromotor skills contribute to children's NWR ability and suggest that important aspects of language learning and consequent language deficits may be rooted in the ability to perform complex sensorimotor transformations.

Key Words: speech motor control, speech production, phonology, language, language disorders, development

Speaking is a remarkably complex motor behavior. In order to produce a highly structured and constrained stream of acoustic energy, more than 50 muscles must rapidly change the shape and position of articulators within the vocal tract (Ackermann & Riecker, 2004; Kent, 2000; Levelt, Roelofs, & Meyer, 1999). The relationship of higher level speech and language abilities to lower level aspects of motor control, planning, and imitation is not well understood, in part because language development is often studied separately from neuromotor development (Iverson, 2010; Iverson & Braddock, 2011). A growing body of recent work shows that motor development has an impact on abilities beyond the purely motor domain; for instance, early emerging motor skills, such as independent sitting or object mouthing, are predictive of consonant production (Iverson, 2010). In typically developing infants, oromotor control at 21 months is associated with language production skills (vocabulary and sentence complexity on the MacArthur–Bates Communicative Development Inventory; Alcock & Krawczyk, 2010). Longitudinal links between measures of articulatory kinematics and the MacArthur–Bates Communicative Development Inventory have been demonstrated in 9- to 21-month-olds, even when age was controlled for (Nip, Green, & Marx, 2011). However, earlier longitudinal studies (e.g., Bates, Benigni, Bretherton, Camaioni, & Volterra, 1979) yielded few, if any, links between gross motor milestones (e.g., the age at which a child started crawling, walking, etc.) and language milestones. The relationship between motor ability and language skill may vary depending on the language skill under study and the measure of motor control used. Gaining an understanding of which nonlinguistic motor skills are relevant when learning language should contribute to a better understanding of the relationship between nonlinguistic and linguistic development.

One basic language skill that might be linked to motor abilities is that of learning to say new words for the first time.

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Although all language is inherently generative, the production of a novel word requires the assembly of a combination of oral gestures in a previously unencountered context. This process can be highly utterance specific and likely involves considerable motor planning (Tremblay, Houle, & Ostry, 2008). Nonword repetition (NWR), a measure that assesses the ability to imitate novel words, is widely used in the clinical diagnosis of language impairment (LI) and as a marker of linguistic ability in genetic studies (Bishop, Adams, & Norbury, 2006). A NWR task involves listening to and repeating a phonotactically legal but nonexistent word like baɪli:dəʊdʒ/ (Bishop, North, & Donlan, 1996) and is thought to assess a child's ability to perceive, encode, remember, and resynthesize new sound combinations. These are abilities that are important not only when learning new oral vocabulary but also for later literacy (Gathercole, Willis, Baddeley, & Emslie, 1994). NWR is a known correlate of vocabulary and a predictor of later vocabulary (Gathercole & Baddeley, 1990; Stokes & Klee, 2009, but cf. Melby-Lervåg et al., 2012).

NWR tasks have been used with many clinical populations (Bishop et al., 2006; Conti-Ramsden, Botting, & Faragher, 2001; Gathercole, 2006; Graf-Estes, Evans, & Else-Quest, 2007; Grant et al., 1997; Laws & Gunn, 2004) and across languages (Sahlen, Reuterskiold-Wagner, Nettelbladt, & Radeborg, 1999; reviewed in Coady & Evans, 2008). However, there is no current consensus about which underlying skills, including sensorimotor skills, contribute to NWR performance, and in what proportion (Coady & Evans, 2008; Snowling, 1981; Snowling, Gouldandris, Bowlby, & Howell, 1986). NWR is most commonly thought of as a measure of phonological short-term memory (Laws & Gunn, 2004; Montgomery, 2004; Perrachione, Del Tufo, & Gabrieli, 2011). This account (for more details, see Gathercole, 2006) posits a direct relationship between NWR and vocabulary; that is, children who are better at remembering long strings of novel, phonologically encoded speech sounds will be quicker to learn the novel phonological forms of new words (Gathercole, 2006). But the accurate repetition of nonwords cannot rely on phonological memory alone. Skills underlying NWR are likely to include speech perception (Coady & Evans, 2008), phonological encoding (Bowey, 2006), and lexical and phonological knowledge (Snowling et al., 1986). In current accounts, the only motor skill thought to influence NWR is maturity of an individual's articulation (Vance, Stackhouse, & Wells, 2005). Furthermore, misarticulation is not thought to contribute greatly to differences in NWR (Gathercole, 2006).

The motor component of NWR, or indeed of producing any novel real word, does not simply relate to the articulation of the sounds in the word but involves converting an auditory representation to a motor sequence in real time, thereby requiring coordination of multiple articulators, such as the lips, tongue, jaw, and palate. (This computational problem has been the focus of models such as Guenther's [2006] Directions Into Velocities of Articulators [DIVA] model). To our knowledge, the relationship of NWR to the ability to plan and sequence these kinds of oral articulatory movements has never been investigated. There is evidence for both individual and developmental differences at this level of oral articulatory control—for instance, the speed of articulator movements is known to increase with age, as speaking patterns become more complex (Goffman & Smith, 1999; Nip et al., 2011; Smith & Zelaznik, 2004). Variability in articulatory movement patterns of the jaw, lips, and tongue also decreases with age, as well as when task complexity is reduced (Goffman & Smith, 1999; Kleinow & Smith, 2006; Smith & Zelaznik, 2004). There is a clear developmental change in the production of nonwords, with children—but not adults—showing motor learning effects on simple nonwords (Sasisekaran, Smith, Sadagopan, & Weber-Fox, 2010) during a period in which children continue to develop articulatory control (Smith, 2006). Such results suggest that individual variation in nonlinguistic oromotor control may in fact be relevant to imitating novel words.

A striking example of a relationship between sensorimotor sequencing and NWR has been demonstrated in a British family (the "KE family"), in which several generations of individuals have a mutation of the FOXP2 gene. This mutation was initially thought to be predominantly associated with severe speech and language impairments, including syntactic processing (Lai, Fisher, Hurst, Vargha-Khadem, & Monaco, 2001); however, family members with and without the mutation showed no overlap in their NWR and oromotor control scores, indicating that they could be distinguished on the basis of these abilities alone (Vargha-Khadem et al., 1998). More generally, children with specific language impairment (SLI) often perform poorly on NWR tasks (Bishop et al., 1996; Conti-Ramsden et al., 2001) and can show subtle but pervasive difficulties with sensorimotor control (Hill, 2001) and motor imitation (Marton, 2009). In a pioneering study, Stark and Blackwell (1997) showed that NWR accuracy in children with SLI was correlated with their oral praxis abilities. In addition, the parents of children with SLI have also been shown to present with poor performance on a task of oromotor skill (Barry, Yasin, & Bishop, 2007). In distinguishing between parents of children with LIs and a control group of parents, oromotor skill was as effective as NWR (Barry et al., 2007), suggesting that NWR deficits could be a genetic risk factor and directly related to speech motor output performance. In that study, however, oromotor skill was assessed by the smooth production of sequential speech sounds in a series of tongue twisters, rather than nonspeech and nonlinguistic oromotor movements.

The evidence reviewed above suggests that oromotor and novel NWR skills may be mechanistically linked in both typical and atypical development. As we have described, NWR is a sensitive marker for LI. If indeed nonlinguistic and nonspeech oromotor skills make a unique contribution to NWR performance, then this would indicate the need for a detailed assessment of not only auditory perception or phonological ability but also oromotor skill in the differential diagnosis and remediation of LI. To explore this issue, in the present study we assessed the contribution of nonlinguistic, nonspeech oromotor control to NWR abilities in two cohorts of school-age children tested on a wide battery of language, cognitive, and auditory tasks.

The Present Study

The oromotor control task we used is a nonlinguistic visual analogue to NWR, in that the child has to encode, retain, and resynthesize a visually presented sequence of movements, much in the same way that one must reproduce an oral sequence when hearing a nonword (see Figure 1 for an example). A crucial point is that because the oromotor control task is nonlinguistic and nonphonetic, phonological memory should not play a role in the oromotor control performance.

In addition to the oromotor control and NWR tasks, we assembled a battery of linguistic and nonlinguistic tasks that are thought to tap into subsets of the cognitive and perceptual processes underlying NWR. The choice of tasks was largely driven by the literature on LIs, both congenital and acquired. Children with LIs—who tend to fare poorly on tasks of NWR (Graf-Estes et al., 2007)—are also apt to show impairments in a range of other skills (Bishop, 2006). For instance, children with LIs show differences from typically developing children in their speed of processing and motor response latency (C. A. Miller, Kail, Leonard, & Tomblin, 2001; Schul, Stiles, Wulfeck, & Townsend, 2004), attentional resource capacity/allocation (Finneran, Francis, & Leonard, 2009; Marton, Kelmenson, & Pinkhasova, 2007; Montgomery, Evans, & Gillam, 2008), and auditory or phonemic discrimination and processing (Bishop, 2006; Fox, Reid, Anderson, Richardson, & Bishop, 2012; cf. Bishop, Hardiman, & Barry, 2012), among other skills. Syntactic comprehension in children with LIs (one of their basic weaknesses; Dick, Wulfeck, Krupa Kwiatkowski, & Bates, 2004) has also been associated with NWR (see Marton & Schwartz, 2003, and Montgomery & Evans, 2009, but cf. Montgomery, 2000). Thus, it is possible that individual differences in these more general skills might contribute to potential correlations between NWR and oromotor control and imitation, not only in children with LIs but also in healthy children. The inclusion of these tasks allows us to factor out individual differences in other abilities that might contribute to NWR–oromotor control and imitation correlations (e.g., sustained attention or speed of processing).

The nonlinguistic tasks we included were designed to measure lower level auditory and motor processing. Tasks were explicitly chosen to be "game"-like and to require very little instruction. First, we included a simple measure of auditory-motor response latency (from Leech, Aydelott, Symons, Carnevale, & Dick, 2007). Second, to characterize individual differences in selective auditory attention and integration, we included a nonlinguistic analogue of the "cocktail party" scenario (Krishnan, Leech, Aydelott, & Dick, 2013; Leech, Gygi, Aydelott, & Dick, 2009). The younger child cohort also completed a measure of sustained attention and response inhibition (Finneran et al., 2009; Marton, 2008; Montgomery et al., 2008).

The linguistic measures were a word reading efficiency task and a test of syntactic comprehension. To measure children's reading, we used the Test of Word Reading Efficiency (TOWRE; Torgesen, Wagner, & Rashotte, 1999b), which correlates strongly with children's overall reading performance (Wise, Sevcik, Morris, Lovett, & Wolf, 2007), vocabulary (Ricketts, Nation, & Bishop, 2007), and NWR ability (Nation & Hulme, 2010). Syntactic comprehension was assessed with a task that reveals considerable individual differences in typically developing children's performance (Dick et al., 2004; Leech et al., 2007). The younger cohort also completed a test of phonemic discrimination (based on Bishop, Brown, & Robson, 1990) to allow us to characterize variance related to fine-grained phonemic discrimination, as opposed to the production-reliant measure obtained using NWR.

Finally, in a subset of children from both experiments, we assessed verbal and nonverbal cognitive ability using online computer-based tasks (normed on over 5,000 pairs of twins; Davis, Haworth, & Plomin, 2009). These were administered via the Internet and used adaptive branching to keep children engaged and limit the number of items to be answered (Haworth et al., 2007).

These tasks were used to investigate the relationship between NWR and oromotor control in two different cohorts. In Experiment 1, we tested a cohort of children between ages 7 and 13 years. We explored the same relationship further in Experiment 2, in 6.9- to 7.7-year-olds, with the additional

Figure 1. An example of a sequential and a simultaneous oral movement.

measures described above. The two cohorts allowed us to present an independent replication of the results in two different age groups while factoring out variance related to an overlapping set of tasks. To maximize statistical power, we also report analyses combining children in both cohorts, and we used this combined sample to assess the contribution of general cognitive ability.

Experiment 1: The Relationship Between NWR and Oromotor Control in School-Age Children

Method

Participants

Forty children participated in this study as part of a larger language battery designed to give an overall picture of a child's auditory, language, and motor ability during the school years. The age of children completing behavioral testing ranged between 7 and 12.5 years, with a mean age of 10.1 years (7 years [n = 2]; 8 years [n = 7]; 9 years [n = 8]; 10 years [n = 12]; 11 years [n = 6]; 12 years [n = 6]). All the children were typically developing right-handed native British English speakers with normal hearing and no history of neurological or speech and language impairments. Hearing status was assessed using parental report, none of the children had had an ear infection for at least 1 year prior to testing, and none of the children had a known history of hearing loss. On the TOWRE, every child achieved an age-normed standard score higher than 80 (M = 110.7, SD = 13.1). The Birkbeck Research Ethics Committee approved the study, and children and parents gave informed and signed consent prior to participation.

Procedure

The behavioral battery comprised six experimental tasks (counterbalanced for order). To ensure data quality, an experimenter monitored children's attention and motivation, making notes on whether they repeatedly looked away from the screen, whether they were talking during trials, and whether they persevered in pressing the same button on the game pad during the auditory tasks. On the basis of these notes, a subset of data from four children was excluded, with a subset of data from three more children excluded because of technical errors. Children were encouraged to take a break between tasks and were given verbal motivation throughout, as well as stickers and a certificate.

Experimental Tasks

Oromotor control task (adapted from Alcock, Passingham, Watkins, & Vargha Khadem, 2000). This task assesses the accuracy of oromotor control by having children imitate simultaneous and sequential orofacial movements (see Figure 1). The choice of the simultaneous movement condition was based on research in acquired speech and language disorders showing that speech-timing problems can be associated with difficulties in simultaneously moving multiple articulators (Alcock et al., 2000; Blumstein, 1998; Blumstein, Cooper, Goodglass, Statlender, & Gottlieb, 1980). A sequential movement condition was included because research has shown that individuals with oral apraxia show deficits in temporo-spatial programming for sequences (Alcock et al., 2000; N. Miller, 1989).

The simultaneous and sequential movement conditions were crossed with the presence or absence of a "memory gap" between observation and execution. In the developmental spatial cognition literature, the imposition of a memory gap can be helpful in unveiling potential individual differences. For instance, it increases error frequency in typically developing children who have mastered a standard no-delay task (Diamond, 1985), and in children with perinatal focal lesions it has helped to reveal subtle but reliable differences in performance that were not evident using a standard immediate drawing reproduction task (reviewed in Stiles, 2011, 2012).

In this task, video-recorded stimuli showed a researcher making oral movements. Each set of oral movements involved three sets of articulators, for instance, "opening the mouth," "sticking out the tongue," and "rounding the lips." Care was taken to ensure that these movements were primarily nonlinguistic and occurred in nonlinguistic contexts (e.g., spreading lips as in smiling, sticking one's tongue out while making a funny face, or rounding lips as when blowing bubbles). Oromotor movements that are visible can typically be associated with a sound. To control for this, we included multiple movements that are typically associated with the same sound (e.g., both opening the mouth wide, or sticking out one's tongue as if at the doctor's office can be associated with saying /a/), thereby ensuring that an auditory strategy was not sufficient to succeed on the task.

As described above, half the trials were presented with a memory gap, whereby there was a 5-s silent period between stimulus presentation and the onset of a xylophone sound, which cued the child to imitate the stimulus. In the other half of trials, the stimulus presentation was immediately followed by the imitation cue (no-gap condition).

Children were seated in front of a camera and computer screen and were instructed to imitate the observed movements after the sound cue. Three practice trials each were provided for the memory gap and no-gap conditions. After every practice trial, children received verbal feedback on their oral movements (e.g., "Good," or "Try to do exactly what she does"). The order of presentation of movements was counterbalanced across children, and all participants performed 20 sets of movements that were video-recorded for subsequent analysis. Two researchers independently scored the videos using the rating system developed by Square-Storer, Qualizza, and Roy (1989). There were three sets of articulators involved in each sequential/simultaneous trial, and each of these three movements was scored between 0 and 2, with a 2 being awarded for a completely accurate repetition, a 1 awarded for each partially correct repetition or for a repetition that was not in the order of the sequence presented, and a 0 awarded for no attempt or an incorrect one. Thus, for each trial, scores could range between 0 and 6. Interrater reliability was at least .85 over all participants and all conditions.

NWR task. We used a standardized measure of NWR to establish a link with the existing literature on NWR and to ensure that our results did not arise because of any task artifacts of a newly developed NWR task. The NWR subtest we used was taken from the Comprehensive Test of Phonological Processing (CTOPP; Torgesen, Wagner, & Rashotte, 1999a). The 18 nonwords from the test (ranging from one to six syllables) were recorded by a native British English speaker and presented to children over headphones (see also Nation, Cocksey, Taylor, & Bishop, 2010, and Nation & Hulme, 2010). Children were asked to repeat the word they heard. Three practice trials were provided, followed by the 18 test items. Example stimuli from the CTOPP include /baɪlɪ:d ʊdʒ/ and /geki:zaɪz kÌd/. The nonwords in the CTOPP do not contain consonant clusters and obey English phonotactics, while varying considerably in terms of phonological complexity. Audio recordings of the children's responses were scored by two independent researchers. Fractional scores were awarded on the basis of accuracy. Interrater reliability was .85.

TOWRE. The Sight Word Reading Efficiency subtest for familiar words from the TOWRE was administered. This is a simple test of fluency, which involves reading a list of progressively complex familiar words within 45 s. A child's score on this test is simply the number of words accurately read.

Complex sentence interpretation task (Leech et al., 2007). This syntactic comprehension task was a two-alternative forced-choice picture-matching task in which children identified the agent in a series of syntactically simple (actives, subject clefts) and complex (passives, object clefts) sentences. Participants heard sentences presented with competing speech mixed in with the target sentence and saw pictures of the sentences' agent and patient. They indicated "who did the action" by pressing the button under the agent's picture. The presentation of simple and complex sentences was interleaved. Percentage correct was calculated separately for simple and complex sentences.

Auditory scene analysis task (Krishnan et al., 2013; Leech et al., 2009). Children matched pictures to environmental sound targets (e.g., the sound of a car starting) that were presented in a single complex natural background (e.g., a noisy street scene), or in one of two backgrounds, each presented to a single ear. Target detection accuracy was calculated separately for targets presented in single or dual auditory backgrounds.

Auditory-motor reaction time (Leech et al., 2007). Children pressed the right or left button on a game pad indicating the ear to which an alert sound was presented. Mean reaction times were used as a measure of auditory-motor processing speed.

Analyses

We conducted initial exploratory analyses by running pairwise correlations between the outcome variable (NWR) and each of the predictor variables: age, oromotor control (with and without the memory gap), reading efficiency, simple and complex syntax, auditory scene analysis in single and multiple background scenes, and auditory-motor processing speed; see Tables 1 and 2 for descriptive statistics and pairwise correlations. In order to understand how well a given task uniquely predicted variance in NWR (given that the predictors themselves were correlated; see Table 2), we then constructed a set of regression models. To avoid model overfitting, we included only those predictors that singly could account for at least a moderate amount of variance in NWR (defined here as a pairwise correlation with NWR of $r \geq .30$). The set of models was made of all possible combinations of predictors; for example, for Predictors A, B, and C, possible models were A and B; A and C; B and C; and A, B, and C.

We report the results of these models ranked by proportion of variance accounted for; all analyses report adjusted R^2 (henceforth *adj.* R^2) to allow for model comparison across different sample sizes and number of predictors (Leach & Henson, 2007); we also indicate which individual predictors contributed significant unique variance to each model. The number of participants per pairwise correlation or regression model is included because not all children completed all tasks; therefore, *n*s differ slightly by experiment. All analyses were conducted in Stata/SE 11.1 using distribution-independent bootstrap techniques (robust for smaller and nonnormally distributed samples) to estimate probability and variance measures (10,000 replication samples per model).

Results

The initial pairwise correlation analysis showed a significant positive relationship between NWR and overall oromotor control score ($r = .48$, adj. $R^2 = .203$, $n = 36$, $p < .0008$). When oromotor control was split by memory gap condition, NWR was significantly correlated with oromotor control score in the gap condition ($r = .45$, adj. $R^2 = .166$, $N = 36$, $p < .0058$) and the no-gap condition ($r = .42$, adj. $R^2 = .140$, $N = 36$, $p < .0126$). There were also significant positive correlations between NWR and complex syntactic comprehension ($r = .46$, adj. $R^2 = .183$, $n = 33$, $p < .003$), and NWR with auditory scene analysis accuracy in the single background condition (henceforth *single ASA*; $r = .31$, adj. $R^2 = .076$, $n = 39$, $p < .026$). All other correlations with NWR were nonsignificant, including age ($p < .90$, perhaps due in part to uneven sampling over the age range; see Table 2 for all pairwise correlations). We then generated robust regression models to test the unique contribution of each of these predictors; the average oromotor control score was used in the model rather than including the individual subscores (with and without the memory gap), given their intercorrelation ($r = .57$).

All four models accounted for significant variance in NWR and are ordered in terms of descending adjusted R^2. The model including oromotor control and complex syntax accounted for the most variance (adj. $R^2 = .237$, $p < .0004$, $n = 31$), with only oromotor control a significant unique predictor ($z = 2.27$, $p < .023$). The model with all three predictors accounted for slightly less overall variance (adj. $R^2 = .211$, $p < .001$, $n = 31$), again with only oromotor control contributing unique variance ($z = 2.15$, $p < .032$). In the model

Table 1. Descriptive variables for tasks and questionnaires used in Experiment 1.

Task	*n*	*M*	*SD*	Min score	Max score	Max possible score
Age	40	10.1	1.5	7.1	12.5	12.5
OMC	36	109.9	4.7	98	119	120
OMC gap condition	36	53.9	2.9	47	59	60
OMC no gap condition	36	56.1	2.4	51	60	60
OMC simultaneous condition	36	57.1	2.1	52	60	60
OMC sequential condition	36	52.8	4.0	45	59	60
NWR	39	15.2	1.5	12	18	18
Reading efficiency	38	73	12.5	50	102	104
Easy syntax	33	.86	.19	.26	1	1
Complex syntax	33	.65	.19	.17	.92	1
AOI in single background	39	.85	.09	.56	.98	1
AOI in multiple backgrounds	39	.74	.12	.48	.91	1
Auditory-motor RT	35	834.5	192.5	435.9	1,258.8	—

Note. Min = minimum; Max = maximum; OMC = oromotor control; AOI = auditory object identification; NWR = nonword repetition; RT = reaction time. Dash indicates "not applicable."

composed of oromotor and single ASA scores (adj. $R^2 = .181$, $p < .003$, $n = 36$), oromotor control again predicted unique NWR variance ($z = 2.93$, $p < .003$). Finally, when only complex syntax and single ASA were included (adj. $R^2 = .167$, $p < .003$, $n = 33$), complex syntax alone predicted unique NWR variance ($z = 2.06$, $p < .039$).

Discussion

These results revealed a relationship between nonlinguistic oromotor control and NWR in a group of 7- to 13-year-old typically developing children. As noted above, this relationship could be driven by the shared demands of the two tasks (both of which require the child to use a dynamic percept to rapidly resynthesize a motor plan that in turn produces a perceptually matching output). It is important to note that this cross-task correlation is strong despite the differences in perceptual input, in that the oromotor task involves nonlinguistic visual input, whereas the NWR involves linguistic auditory input. The cross-task correlation is unlikely to be driven by individual differences in short-term memory alone, because performance in the oromotor gap and no-gap conditions both significantly correlated with the NWR score. If this result were due to individual differences in working memory, one would not expect that the no-gap condition scores to predict NWR scores, because working memory load was relatively minimal. The correlation between the two tasks regardless of memory gap suggests that the common nonlinguistic skills of motor sequencing, planning, and imitation play a significant role in NWR performance in school-age children.

A correlation also emerged between NWR and complex syntax. A relationship between complex syntactic constructions and NWR has been demonstrated in children with SLI (Montgomery & Evans, 2009), but to our knowledge never before in typically developing children. The demands of our syntactic task (in particular, the perceptual and attentional masking components; Leech et al., 2007) may have helped unveil this relationship in typically developing children.

One limitation of this first experiment was the somewhat uneven sampling over age, with more than half the children age 9 or older. The undersampling of younger children may have contributed to the near-ceiling performance on simultaneous oromotor movements (see Table 1) as well as the lack of relationship between reading efficiency and NWR (see Nation & Hulme, 2010). In addition, the battery of

Table 2. Correlations between NWR and other experimental measures from Experiment 1.

Variable	1	2	3	4	5	6	7	8	9
1. Age	—								
2. OMC	.16	—							
3. NWR	.02	.48**	—						
4. Reading efficiency (TOWRE)	.50**	.24	.24	—					
5. Complex syntax	.50**	.39	.46**	.49**	—				
6. Easy syntax	.34	.04	.06	.33	.32	—			
7. AOI in a single background	.43**	.28	.31*	.05	.44**	.13	—		
8. AOI in multiple backgrounds	.19	.31	.17	.16	.46**	.13	.47**	—	
9. Auditory-motor RT	−.10	−.06	−.13	−.36*	−.29	−.39*	−.13	−.08	—

Note. TOWRE = Test of Word Reading Efficiency.
*$p < .05$. **$p < .01$.

tasks in the first experiment did not allow us to test whether the relationship between oromotor and NWR skills might be mediated by individual differences in cognitive control or speech sound perception. Therefore, in the second experiment we tested an independent cohort of younger (~7 years old) children on a similar battery of linguistic and nonlinguistic measures as well as a test of executive function (a no-go task) and phonemic discrimination (AX discrimination task).

Experiment 2: The Relationship Between NWR and Oromotor Control in Younger School-Age Children

Method

Participants

Children were recruited via invitation on the basis of their previous participation in a longitudinal infant study (Karmiloff-Smith et al., 2010) for the purposes of another experiment, but whom we also tested in the present one. Thirty-seven typically developing children with normal hearing (all British English speakers) between the ages of 6.9 and 7.7 years (22 males, 15 females) responded to the invitation and participated in Experiment 2. Every child achieved an age-normed standard score higher than 80 on the TOWRE (M = 113.22, SD = 11.9). The Birkbeck Research Ethics Committee approved the study, and children and parents gave informed and signed consent prior to participation.

Procedure

A slightly modified battery from Experiment 1 was constructed, and the order in which children completed the tasks was kept constant. Experimenter notes were made on children's attention as before, and on this basis a subset of data from two children was excluded from the analyses. Two other children were excluded for technical reasons, and one child did not want to participate in the oromotor task. Overall, children were encouraged to take breaks between tasks and were given general verbal motivation throughout. They were also awarded stickers as they finished tasks.

The oromotor task was modified to include only sequential movements (because most of the participants in the previous experiment performed close to ceiling on the simultaneous movements). The children therefore completed 10 sequential movements with a 5-s gap and 10 sequential movements with no gap.

The NWR task, the Sight Word Reading Efficiency subtest from the TOWRE, and the auditory-motor reaction time task were completed using the same procedure as in Experiment 1. The complex sentence identification task and the auditory scene analysis were modified to create the option for a break halfway through the task. A phonemic discrimination task (adapted from Bishop et al., 1990) measured children's accuracy and reaction time for detecting differences between pairs of nonwords. Sixty items were devised, half consisting of two identical nonwords (e.g., /bif/–/bif/) and the remainder consisting of two acoustically similar nonwords that differed by one phoneme on the initial or final consonant (e.g., /raʊb/ → /raʊs/). Phonemes could differ by one feature (e.g., /b/–/d/), two features (e.g., /b/–/t/), or three features (e.g., /b/–/s/). Children heard the nonwords through headphones and responded by pressing buttons on a game pad to indicate whether the pair of words were the same or different. Reaction times and accuracy were measured. Children also completed a test of executive functioning, the Sustained Attention to Response Task (Manly, Davison, Heutink, Galloway, & Robertson, 2000). Children saw a series of digits (interstimulus interval = 1.15 s) and responded by pressing a button on a game pad for every digit except 3. The percentage of trials accurately inhibited was scored for this task.

As in Experiment 1, we conducted the initial analyses by running pairwise correlations between the outcome variable (NWR) and each predictor variable, with age not included as a predictor because of the narrow age range. In the second stage, we constructed a family of regression models using all combinations of variables that were pairwise correlated with NWR at $r \geq .30$; these are reported exactly as in Experiment 1.

Descriptive statistics for children's performance on all tasks are provided in Table 3.

Results

As in Experiment 1, there was a pairwise correlation between NWR and overall oromotor control (r = .40, adj. R^2 = .136, n = 34, p < .0106); split by memory load, NWR was significantly correlated with the oromotor no-gap condition (r = .40, adj. R^2 = .134, n = 34, p < .0110) and with the gap condition (r = .30, adj. R^2 = .058, n = 34, p < .0487). NWR was also significantly correlated with reading efficiency (e.g., TOWRE, r = .32, adj. R^2 = .077, n = 34, p < .0333) and phonemic discrimination (r = .38, adj. R^2 = .113, n = 30, p < .0103).

All other correlations with NWR were nonsignificant (see Table 4). As in the analyses from Experiment 1, we created regression models using all four combinations of predictors with pairwise $r \geq .30$ (oromotor control score, reading efficiency, and phonemic discrimination). All accounted for significant variance in NWR and are ordered in terms of descending variance accounted for, with unique contributions noted. The regression model including oromotor control and reading efficiency accounted for the most variance (adj. R^2 = .217, p < .0023, n = 34), with oromotor control (z = 2.69, p < .007) and reading efficiency (z = 2.26, p < .024) predicting unique variance. The model with all three predictors accounted for slightly less overall variance (adj. R^2 = .208, p < .001, n = 29), with no predictor accounting for unique variance. In the model composed of oromotor and phonemic discrimination (adj. R^2 = .170, p < .003, n = 29), again no single predictor accounted for unique variance. Finally, when only reading efficiency and phonemic discrimination were included (adj. R^2 = .151, p < .003, n = 30), phonemic discrimination predicted unique NWR variance (z = 1.96, p < .05).

Discussion

As in Experiment 1, we found a significant relationship between oromotor control and NWR performance, thus

Table 3. Descriptive variables for tasks and questionnaires used in Experiment 2.

Task	*n*	*M*	*SD*	Min score	Max score	Max possible score
Age	37	7.3	0.2	6.9	7.7	n/a
OMC	36	101.2	7.3	82	113	120
OMC gap condition	36	48.4	5.2	33	57	60
OMC no gap condition	36	52.8	3.5	45	58	60
NWR	35	12.6	1.8	8.8	15.8	18
Reading efficiency	36	51.9	14.9	16	69	104
Easy syntax	35	.76	.19	.34	1	1
Complex syntax	35	.38	.14	.21	.83	1
AOI in a single background	30	.74	.12	.30	.90	1
AOI in multiple backgrounds	30	.65	.12	.34	.80	1
Auditory-motor RT	36	976.6	187.3	685.7	1,383.5	—
Phonemic discrimination RT	32	1,576.6	198.0	1,258.8	2,047.6	—

Note. Dash indicates "not applicable."

providing additional evidence for a link between nonlinguistic oromotor skills and NWR performance. Also as in Experiment 1, both oromotor no-gap and gap performance were significantly correlated with NWR, suggesting that working memory differences alone do not drive this relationship, because the gap condition places greater demand on working memory as compared to the no-gap condition.

In concordance with results from Nation and Hulme (2010), reading efficiency, as measured by the TOWRE, was also a significant predictor of NWR in this cohort. Also, as would be expected given previous findings, children's phonemic sensitivity (as indexed by the phonemic discrimination task) was significantly correlated with NWR. However, unlike results from Experiment 1, complex syntax was only marginally correlated with NWR (see Table 4).

Combined Data From Experiments 1 and 2

To account for other factors that might drive the relationship between oromotor control and NWR, we combined the data from Experiments 1 and 2 that contained overlapping subsets of experimental test measures. All statistical models included cohort[1] as a binary predictor variable (7- to 12-year-olds in Experiment 1; 7-year-olds in Experiment 2).

We first ran a regression model on all 70 children who had successfully completed oromotor and NWR tasks. Together, oromotor control and cohort accounted for considerable variance in NWR (adj. $R^2 = .515$, $p < .0001$), with significant unique variance accounted for both by oromotor control ($z = 3.75$, $p < .001$) and cohort ($z = 4.04$, $p < .001$), whereby the 7-year-old cohort was significantly less accurate than the 7- to 12-year-olds (see Panel A of Figure 2). A test for homogeneity of slopes for oromotor control over the two cohorts did not show significant differences ($p > .4$).

Next, we built an omnibus regression model with data from the 55 children in Experiments 1 and 2 who completed an overlapping subset of experimental measures: oromotor control, reading efficiency, syntax (collapsed across simple and complex conditions), auditory scene analysis (collapsed across background conditions), and auditory-motor processing speed. (The syntax and auditory scene analysis submeasures were collapsed because they were moderately to strongly correlated across the larger sample: simple vs. complex syntax, $r = .43$, single vs. dual background auditory scene analysis, $r = .74$). Cohort was also included in the model. The omnibus model predicted considerable variance in NWR scores (adj. $R^2 = .550$, $p < .0001$), with oromotor control significantly accounting for unique variance ($z = 3.22$, $p < .001$; see leverage plot in Panel B of Figure 2), along with reading efficiency ($z = 1.97$, $p < .049$).

Contribution of General Cognitive Abilities

Finally, to determine whether general cognitive factors might underlie the relationship between oromotor control and NWR, all participants were invited to complete the at-home online standardized tests described above. The measures included two nonverbal reasoning tests: (a) Raven's Standard Progressive Matrices (Raven, Court, & Raven, 1996) and (b) the Picture Completion subtest of the Wechsler Intelligence Scale for Children, Third Edition, U.K. version (Wechsler, 1992). Two verbal measures were also included: (a) the General Knowledge (Multiple Choice Information) and (b) Vocabulary Multiple Choice subtests of the Wechsler Intelligence Scale for Children, Third Edition, U.K. version (see Table 5 for descriptive statistics and Table 6 for cross-task correlations). A subset of each group from Experiments 1 ($n = 28$) and 2 ($n = 17$) completed these online tasks and were combined into a single data set. Because the subscale scores were moderately to strongly intercorrelated (see Table 6), we reduced the four scales to two principal components, accounting for 77% of score variance.

Oromotor control, cohort, and the two principal components from the standardized tests were entered into the

[1]Across our two experimental cohorts, age was nonnormally distributed and highly positively skewed and therefore nonideal as a predictor variable. The binary variable of cohort was used in lieu of age because it accounted for the majority of variance in age (adj. $R^2 = .64$, $p < .0001$); it also controlled for the slight differences in test battery composition and procedure across the two experimental cohorts. The pattern of results observed when cohort was entered did not differ from the results obtained when continuous age was entered.

Table 4. Correlations between NWR and other experimental measures from Experiment 2.

Variable	1	2	3	4	5	6	7	8	9	10
1. Age	—									
2. OMC	–.30	—								
3. NWR	–.03	.40**	—							
4. Reading efficiency	.20	.06	.32*	—						
5. Complex syntax	.14	–.12	.26	.04	—					
6. Easy syntax	.07	.01	.14	.08	.36*	—				
7. AOI in a single background	.03	–.09	.07	–.19	.14	.14	—			
8. AOI in multiple backgrounds	.26	.08	.28	–.11	.01	.23	.68***	—		
9. Auditory-motor RT	–.20	–.21	–.22	–.18	–.09	–.10	–.12	.01	—	
10. Phonemic discrimination RT	.27	.24	.38*	.15	.34	.22	.04	.17	.16	—

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

regression model as predictors for NWR. This model was significant (adj. R^2 = .482, p < .0001), revealing a significant effect of oromotor control (z = 2.73, p = .006; see leverage plot in Panel C of Figure 2), with no other factor contributing unique variance.

Discussion

Across all participants, nonlinguistic oromotor control was the experimental predictor accounting for most variance in NWR, with additional unique variance being predicted by reading efficiency. Inclusion of our standardized measures (including Raven's Standard Progressive Matrices) in the regression model did not eliminate oromotor control as a significant predictor of NWR performance. This result might be considered as further indirect evidence that individual differences in memory (and working memory) are not the primary contributor to the NWR–oromotor relationship. Performance on Raven's Standard Progressive Matrices tends to be associated with measures of memory (rs = .18–.30) and working memory (rs = .30–.62; Unsworth & Engle, 2005, but cf. Engel de Abreau, Conway, & Gathercole, 2010) and therefore might be expected to remove at least some of the variance associated with memory skills.

General Discussion

Separate and combined results from two experiments showed that typically developing children's ability to imitate novel nonlinguistic oromotor sequences is predictive of their ability to imitate novel, phonotactically legal nonwords. This relationship is independent of age and broader language skills and is seemingly not driven by skill in reading, attentional ability, or complex auditory perception. Furthermore, our results indicate that this relationship is independent of more general cognitive abilities, because nonlinguistic oromotor control remained a significant predictor of NWR performance when standardized cognitive test scores were included in the regression model.

In particular, our findings challenge a long-standing assumption in the literature: that NWR tasks index only

Figure 2. Oromotor (OM) scores predict nonword repetition (NWR) proficiency. Panel A: Whole regression plot of raw OM versus NWR scores, combined across cohorts from Experiment 1 (7- to 12-year-olds) and Experiment 2 (7-year-olds). Regression lines show the best fit for OM to NWR scores with cohort in model; the offset in the lines shows the effect of cohort. Panel B: Plot of OM leverage by NWR leverage residuals in a regression model that includes all experimental measures and the cohort. The distance between each point and horizontal line shows the residual error without OM included in model; the fit line shows the parameter estimate for OM. Panel C: Plot of OM leverage by NWR leverage residuals in a regression model that includes OM, cohort, and the first two principal components of the standardized measures of general cognitive ability.

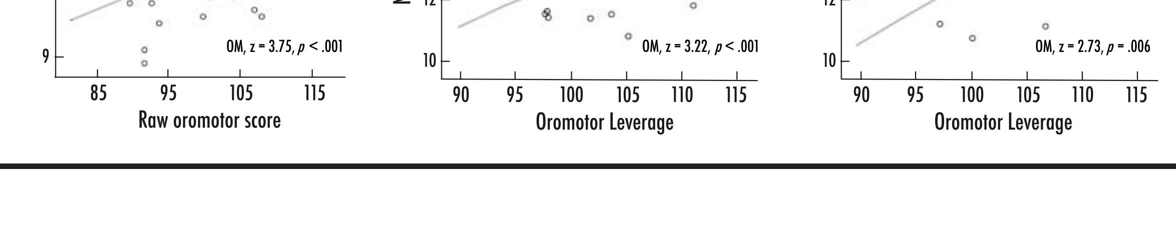

Table 5. Descriptives for tasks of general cognitive functioning.

Test	*n*	*M*	*SD*	Min score	Max score
Raven's Progressive Matrices	46	10.5	4.6	0	18
WISC–III					
General Knowledge	46	20.4	6.9	9	40
Vocabulary	46	35.6	8.7	18	52
Picture Completion	45	17.0	5.3	2	30

Note. WISC–III = Wechsler Intelligence Scale for Children, Third Edition, U.K. version.

Table 6. Correlations between standardized test scores.

Test	1	2	3	4
1. Raven's Progressive Matrices	—			
2. WISC–III General Knowledge	.55***	—		
3. WISC–III Vocabulary	.43**	.58***	—	
4. WISC–III Picture Completion	.38**	.30*	0.44**	—

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

phonological storage or phonological working memory. In contrast, we have demonstrated that these tasks also involve nonlinguistic motor skills and planning. These results provide experimental confirmation of Snowling et al.'s (1986) suggestion that different types of deficits might result in NWR impairment, for example, phonological encoding, storage, or—most important for the present study—motor execution. Our findings also fit with genetic studies suggesting that "genes that put the child at risk for communicative problems also affect motor development, with the association being most evident when speech production is affected" (Bishop, 2002, p. 56). Moreover, our results extend Stark and Blackwell's (1997) original findings of a correlation between NWR and oral praxis in children with SLI.[2]

On the basis of our findings, we suggest that a developmental assessment of oromotor control may be a helpful differentiator in studies of LI, allowing researchers to parse out differences related to oromotor control from phonological perception/sensitivity. Given the prevalence of motor coordination difficulties in children with LI (some estimates indicate they are up to 10 times more likely; Hill, 1998; Iverson & Braddock, 2011), oromotor control may contribute even more to the NWR performance of children with LI than is the case in typically developing children (also see Archibald & Gathercole, 2007). In designing such assessments, a caveat to bear in mind is that previous studies have shown little to no relationship between language production skills and the ability to synthesize single oral movements but instead a tighter relationship with the ability to combine and coordinate multiple oral movements (Alcock et al., 2000; Alcock & Krawczyk, 2010).

Although our results show that individual differences in the control of oromotor skills predict variation in one measure of language production well into the school years, further research is needed to untangle the relative contribution to this relationship of individual differences in oromotor imitation and oromotor dexterity. Our study investigated children's accuracy in imitating a complex oral movement seen for the first time and focused on overall sensorimotor transformation ability. However, performance on our task involves both encoding of the stimulus and motor control and planning. To separate out the influence of dexterity and planning from that of memory and imitation, it would be helpful to include direct measures of motor control that assess articulatory variability (Heisler, Goffman, & Younger, 2010; Sasisekaran et al., 2010; Walsh, Smith, & Weber-Fox, 2006). The effector specificity of the NWR–oromotor relationship could also be examined by comparing oromotor and gestural sequencing ability (Zelaznik & Goffman, 2010). Finally, although it is unlikely that shared demands on working memory drive the NWR–oromotor relationship (for the reasons discussed after each experiment), inclusion of measures such as digit span would be useful in clarifying its role.

More broadly, our results are also relevant to recent discussions of the possible links between motor skills and language, including models that posit a role for the motor system at multiple levels of language representation (Skipper, Nusbaum, & Small, 2006). Until now, most research into the development of motor–language relations has focused on manual gesture or motor milestones in early childhood (see Iverson & Braddock, 2011). As Goffman (2010) suggested, articulatory and linguistic production units may interact in complex, dynamic ways throughout development. The links between articulatory and linguistic production may also be driven in part by shared reliance on more basic procedural and sequence learning skills (Ullman & Pierpont, 2005; also see Evans, Saffran, & Robe-Torres, 2009, for a discussion of these issues).

In conclusion, our findings are of importance with respect to language acquisition, both clinically and theoretically. Clinically, they indicate that NWR is not simply an indicator of phonological proficiency but also an index of nonlinguistic oromotor skill and planning. We speculate that quantifying the contribution of oromotor skill to NWR may help identify a potential risk factor for LI. In this case, oromotor control would not be the only risk factor to influence performance but might act as in combination with other risk factors. Theoretically, our findings clearly illustrate the need to study language development in an embodied context in order to fully understand developmental relationships between nonlinguistic and linguistic systems.

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[2]Sahlen et al. (1999) did not find such a correlation in children with SLI, perhaps because most of their participants performed at ceiling on a screening tool with only five nonspeech single movement items.

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