Motor control for speech exhibits developmental trends in which children demonstrate poorer control than do young adults. In particular, studies examining various measures of speech performance have shown that children tend to be less accurate and more variable than adults during the production of speech (Eguchi & Hirsh, 1969; Kent & Forner, 1980; Sharkey & Folkins, 1985; Smith, Goffman, & Stark, 1995; Tingley & Allen, 1975; however see Stathopoulos, 1995 for an alternative interpretation of these findings). Although children may be less accurate and more variable than young adults, the nature and source of the motor control differences, especially the variability, remains poorly understood, partially because of the limited number of studies in the literature.

An early acoustic study of consonant durations by DiSimoni (1974) revealed that children exhibited greater variability than adults, with older children demonstrating performance more similar to that of adults than did the younger children. However, this study examined a limited
portion of the acoustic signal and provided little insight into the source of the differences. A later study revealed that children produced overall longer segment durations in addition to exhibiting greater variability, leading researchers to propose that the variability might be attributed to longer overall durations rather than development instability per se (Kent & Forner, 1980). This suggestion was supported by subsequent research that showed a relationship between segment durations and variability when adults produced speech at varying rates (Adams, Weismer, & Kent, 1993). To address this issue directly, Smith (1994) examined the relationship between duration and variability in children’s speech. He failed to find a strong relationship among these variables and concluded that children exhibited segment durations that more closely match those of adults while exhibiting greater performance variability. Of course, these acoustic studies allow one to only infer the underlying motor control capabilities of the participants. Kinematic studies provide a more direct way to assess the mechanism underlying speech motor control development.

Sharkey and Folkins (1985) reported that children exhibited greater variability on measures of movement durations and amplitudes of lip and jaw movement during speech production. Smith and Goffman (1998) examined lower lip plus jaw movements during repeated productions of short phrases (e.g., “Buy Bobby a puppy”). The movement traces were time and amplitude normalized by subtracting the mean and dividing by the standard deviation. To examine variability of the underlying movement pattern (once variations in time and amplitude were removed by the normalization procedure), the spatiotemporal index (STI) was obtained by computing standard deviations across 15 repetitions. A high STI reflects greater variability in the normalized traces, whereas a low STI reflects a more stable movement pattern across trials. Mean movement durations were also obtained.

Consistent with earlier studies, Smith and Goffman (1998) reported that the youngest children exhibited longer movement durations as well as higher STIs or greater movement pattern variability. They further noted that children exhibited a qualitatively different movement pattern from that of the adults, irrespective of overall duration or variability, in that the children spent more time on the beginning of utterances than the adults. The authors concluded that the variability observed in children likely reflects instability in the central nervous system. Furthermore, the different underlying movement pattern produced by children was interpreted as reflecting a different motor control strategy (Ballard, Zimba, Robin, & Woodworth, 2001; Smith & Goffman, 1998). These authors suggest that children might depend more on feedback to guide movements, particularly during the onset of movements, leading to a different overall movement pattern as well as greater variability throughout the movement.

Similar findings have been reported during nonspeech oral tasks, which allow for study of motor control of the orofacial and laryngeal systems in the absence of linguistic demand (Ballard et al., 2001; Folkins et al., 1995). Using a visuomotor tracking paradigm, Ballard et al. (2001) found that nonspeech motor control, specifically for temporal parameters, of the orofacial and laryngeal systems was less accurate and more variable in children than in young adults.

Developmental variability is typically interpreted as reflecting poorer control over the motor planning or execution systems (Smith & Goffman, 1998). However, other factors may also contribute to variability, including flexibility in the motor system and adaptation or learning (Schmidt, 1975; Sharkey & Folkins, 1985). For example, adult speakers exhibit variability in the pattern and extent of muscle activation (Folkins, 1981; Kuehn, Folkins, & Cutting, 1982; Smith, Zimmerman, & Abbas, 1981) even when environmental conditions are kept constant.

One can also consider developmental variability within the framework of specific models of motor control. One model cited in recent investigations of speech motor control (e.g., Ballard et al., 2001; Clark & Robin, 1998) is Schmidt’s (1975, 1976) schema theory of motor control. This model is one of the most fully developed motor programming models in the literature. Within this framework, motor programs are mental models or “memories” for movements that are invoked in the planning and production of movements. Schmidt incorporated the notion of generalized motor programs (GMPs), which allows for a single motor program to be used for the production of related movements by applying temporal and amplitude parameters that specify the speed and size of individual movements. The greatest support for this model has been the finding that several experimental variables, such as frequency of feedback and practice conditions, differentially affect the accuracy of the underlying GMP and the assigned temporal and amplitude parameters (Heuer, Schmidt, & Ghodsiian, 1995; Wulf, Lee, & Schmidt, 1994; Wulf, Schmidt, & Deubel, 1993).

Schmidt’s schema theory proposes that schemas for movements develop in the same manner as other mental schemata: through experience or practice. During initial phases of development, movement is characterized by variability as different parameters and/or GMPs are selected over multiple trials. As schemas become more refined, GMPs and parameters are assigned with greater accuracy and consistency; thus performance variability is reduced. Variability is also manifest during development, as physical changes in the articulators and
nervous system require the modification of parameter assignments (e.g., to compensate for changes in the distance between articulators and/or the efficiency of motor units).

At this point it is useful to reexamine the Smith and Goffman (1998) findings within the framework of Schmidt’s schema theory. The method used by Smith and Goffman is very similar to that typically used to study GMPs. Wulf et al. (1993) described a procedure by which movement traces were systematically rescaled both temporally and by amplitude to “best match” a target movement pattern (as calculated by RMS error). The degree to which the movement trace must be rescaled temporally and by amplitude reflects the accuracy of the temporal parameter and amplitude parameter assignments, respectively. The error remaining after the movement trace has been optimally rescaled (residual RMS error) reflects the accuracy of the GMP. That is, once the variations in absolute amplitude and duration are removed, what remains reflects the relative timing, which is determined by the GMP. The standard deviation of the residual RMS error computed over multiple trials is called variable error (VE), and it is similar to the STI used by Smith and Goffman. Thus, within the framework of Schmidt’s (1975) schema theory, the results of the Smith and Goffman study suggest that children exhibit greater variable error in the GMP, or a less stable motor program, than adults. The method used by Smith and Goffman does not allow us to assess parameterization accuracy or stability, because duration and amplitude variations were removed but not examined.

Additional information about children’s ability to accurately and consistently assign temporal and amplitude parameters as well as generalized motor programs may lead to greater understanding of the development of motor control for speech. The current study begins to address these issues through the examination of performance during a nonspeech oral task. We examined GMP and parameterization accuracy and stability of children and adults producing a nonspeech labiomandibular movement. Modeled after motor learning experiments (e.g., Wulf et al., 1993) and our initial work (Clark & Robin, 1998), participants attempted to match a visual target by moving their lower lip and jaw in a series of opening and closing gestures (see Method). Although researchers continue to disagree about the relationship between control for speech and control for nonspeech movements (see Folkins et al., 1995; Robin, Solomon, Moon, & Folkins, 1998; and Weismer & Liss, 1991 for the opposing view), the primary rationale for using a nonspeech task in this study is that the model of interest relates to motor control across functional systems. The principles derived from the model are assumed to apply similarly to speech and nonspeech movements, and the findings of the study will speak to the usefulness of the model for explaining developmental variability. Additionally, we believe it advantageous to examine movement control when a specific movement target is the goal. As pointed out by Stathopoulos (1995), speech goals require the interaction of several speech subsystems whose individual components may not adequately reflect the functional outcome of the whole. In the present study, we measured labiomandibular control when the goal was accuracy of labiomandibular movement. In summary, we offer the following rationale for using a nonspeech task in this study: (a) We believe that certain motor programming principles are common to speech and nonspeech oral control. (b) We wished to reduce the constraint of interaction among speech subsystems by studying labiomandibular movements when the goal is indeed labiomandibular. (c) We wished to gain information about the basic motor control capabilities of the structural system with which speech is shared. Specifically, the purpose of the current study was to examine the accuracy and stability of three aspects of oral motor control: GMP assignment, temporal parameterization, and amplitude parameterization in children and adults. We predicted that children would be less accurate and more variable in the assignment of GMPs and parameters than adults and that the task demand of changing overall duration would produce greater differences in the temporal than the amplitude parameter.

**Method**

**Participants**

Forty individuals participated in the experiment. Twenty men and women between the age of 20 and 40 years (mean age = 25.4 years) and 20 children between the age of 6 and 12 (mean age 8.1) were recruited. The adult group included 8 men and 12 women, and the child group included 10 boys and 10 girls. With the following exceptions, all participants reported a negative speech and language and neurological history: One adult participant reported a single episode of loss of consciousness (less than 15 minutes) following a motor vehicle accident 8 years earlier. Two adult participants reported developmental articulation errors, although neither participant reported receiving intervention. All participants reported normal or corrected-to-normal vision.

**Task and Apparatus**

Participants were seated in front of computer monitors on which target movement patterns were displayed. Participants’ heads were stabilized in all planes with a wall-mounted cephalostat to reduce whole-head movement artifact. Inferior-superior labiomandibular movements produced during experimental trials were
transduced with a strain gauge attached to lower lip at the vermilion border. The strain gauge was inserted into a small section of rubber tubing attached to the lower lip by double-sided adhesive tape, allowing for free lateral movement of the gauge during vertical displacement. The signal was amplified so that 5mm displacement equaled a 1-volt change. The amplified signal was digitized at 200 Hz by a Metabyte Dash 16 analog-to-digital converter and stored directly to the hard drive on a personal computer.

The experimental task was similar to that described by Clark and Robin (1998) and Wulf et al. (1993). Participants were required to produce labiomandibular opening-closing movements with specific spatiotemporal goal movement patterns. Three target movement patterns were used, each with the same relative timing and same amplitudes but with different absolute movement times (see Figure 1). The target waves were generated by a time series of sine and cosine terms, a portion of which was selected for the target movement patterns. For each target movement pattern, the participant began with the lower lip in a slightly opened position and then produced a sequence of opening-closing-opening-closing movements to produce the target pattern, attempting to match the target in both space and time. The total target movement times for the three versions used (Versions A, B, and C) were 1238, 1073, and 743 ms, respectively. The amplitude of the target (from lowest to highest point) was 15 mm.

**Procedure**

Participants were provided with verbal and written instructions in the task. Following the instructions, the participants performed 10 familiarization trials using Version B. The participant’s performance was discussed after each familiarization trial to ensure the participant knew how to interpret the feedback that was to be provided during experimental trials. All participants demonstrated understanding of the task as evidenced by improved performance over the course of the familiarization trials. Moreover, visual inspection of the movement traces revealed that each subject was performing the task and producing the required movement and not a random or completely different waveform. During testing all subjects attended to the screen and were judged to be active participants in the experiment. A few of the children commented that it was a fun task, not unlike a computer game with their lip.

Each participant completed a total of 90 experimental trials. Before each trial, one of the target movement patterns was displayed for 4 s on a 14-inch computer monitor. A letter (A, B, or C) displayed in the upper left corner of the screen identified the specific target wave.

The target and letter were then removed and replaced by two solid lines on the left margin on the screen. A white solid line in the center of the screen represented the starting position for the movement, and a blue solid line represented the strain gauge’s actual position. The participant was required to align the two lines by opening the lower lip and jaw to the starting position. When the criteria for alignment was met (within 200 convertor units—approximately .5 mm—for 50 ms), the two lines disappeared and a 400 Hz tone sounded for 100 ms, indicating that the movement should begin. The participant’s task was to produce a labiomandibular movement that modeled the target pattern presented. During the movement, the screen remained blank.

Detailed instructions, in simple language, were provided to each participant before and during the familiarization trials. Participants were encouraged to match the target pattern as closely as possible, both in shape and size, by moving their lip and jaw up and down in the pattern displayed. Specifically, a participant was told to “draw the shape” with his or her lip.

Following 63% of trials, participants received knowledge of results (KR) feedback. That is, after a 2-s interval, during which the participant’s movements were transduced, digitized, and recorded, KR feedback was presented by superimposing the participant’s actual movement trace (displacement over time) over that of the target pattern. The target pattern was displayed in white (on a black background), and the participant’s pattern was displayed in blue. Additionally, the participant’s trace began farther to the left and continued farther to the right than the target pattern, allowing the two patterns to be easily distinguished. The participant’s movement pattern was displayed exactly as it was recorded, but the target pattern was shifted to
the left or right so that the first zero crossing of both the target and movement patterns were aligned. The movement and target patterns were displayed in their complete forms simultaneously. The RMS deviation between the two patterns (after the target pattern was realigned) was calculated and displayed in the upper right corner of the screen. KR feedback was “faded” in that the relative KR frequency was systematically reduced across trials. Specifically, in the first three blocks, KR was presented on five of the six trials; during the next six blocks, KR was presented on four of the six trials; and during the final six blocks, KR was presented on three of the six trials. This yielded an average KR frequency of 63%. When presented, KR remained on the screen for 5 s. The participants were instructed in how to interpret the feedback during the familiarization trials. Specifically, each was told which trace was the target and which was his or her movement trace and that accurate “matching” was reflected by lower residual RMS scores. “See this line; that is you moving and this other one is the target. Look at this number, the lower the number the better you are doing.”

Experimental trials of Versions A, B, and C were presented in blocks of six trials, in which each version was performed six times before a switch to another version. The order of task versions was randomized, with the restriction that each version appeared once in each three-block sequence. Each participant completed five sets of blocked trials for a total of 90 trials.

**Preliminary Analyses and Dependent Measures**

**Unit Structure**

As noted by Wulf, Schmidt, and Deubel (1993), in order to interpret the results of the GMP and parameterization analysis, it is first necessary to determine that a single GMP controlled the movements observed. For the scaling procedures used, it is assumed that the movement has a single, rescalable rate parameter (Wulf et al., 1993). It is further assumed that rate and amplitude parameters are constant across a given action, although they may vary across actions. Such a single programmed unit (Schneider & Schmidt, 1995; Young & Schmidt, 1991) is defined as a single GMP with a time-scalable rate parameter.

Young and Schmidt (1991) described movements that are controlled by two or more units (Type I movements). With such movements, it would be inappropriate to rescale the entire movement with a single scaling procedure as described above, because it would not be expected that a single proportionate scaling would be observed across two or more units. Thus, before employing the rescaling procedure to examine GMP and parameterization accuracy, it was first necessary to examine the unit structure of the observed movements.

The first step in the unit structure analysis was to generate the velocity-time function for the movement waves and to identify seven “landmarks” defined by peaks, zero crossings, and valleys in the velocity trace. Beginning with the first landmark, the landmarks were labeled A through G. The interval in time from the first zero crossing to each of the landmarks was measured and recorded. The within-subject correlations among all possible pairs of measures were computed (df = 178). As described by Young and Schmidt (1991), the correlations between the first landmark and the remaining landmarks (e.g., A-B, A-C, A-D, etc.), as well as between the last landmark and the preceding landmarks (e.g., A-G, B-G, C-G, etc.) and between contiguous landmarks (e.g., A-B, B-C, C-D, etc.) were examined. The assumption is that if the movement trace represents a single structural unit, then the correlation between the landmarks should be near 1.0. However, if the movement is governed by two or more GMPs, the correlations between landmarks that fall under the governance of separate GMPs should fall towards zero. Wulf et al. (1993) pointed out that the absolute size of the correlation is not critical, because this calculation may be affected by factors unrelated to the unit structure. Rather, it is the abrupt change in correlation between contiguous landmarks that signal that a movement represents more than one unit structure. (See Young & Schmidt, 1991, for complete discussion of this analysis technique.)

**Temporal and Amplitude Scaling and Residual RMS Error**

In the manner described by Wulf, Schmidt, and Deubel (1993) and Clark and Robin (1998), temporal and amplitude scaling were conducted to determine the accuracy of GMP and amplitude and timing parameters. The rescaling algorithm was as follows: For each trial, the target wave was temporally rescaled (compressed or expanded) from .4 to 1.75 in increments of .09. Additionally, the target wave was temporally offset from 1 to 200 samples (5 to 1000 ms) in intervals of 13 samples (65 ms). For each combination of scaling and offset, an amplitude offset was also applied. The amplitude offset was determined by obtaining the means of the target and movement pattern and offsetting the target pattern so that the means were equal. Following the application of the amplitude offset, RMS error was calculated. The combination of temporal offset and scaling that resulted in the smallest RMS error was selected as a “best match.” To further refine this measure, two refinement passes were completed in which the interval of samples which contained the “best match” were reanalyzed in 15 intervals (i.e., .013 intervals of temporal scaling factor and
8.7 ms intervals of temporal offset). After the final refining pass, the temporal scaling factor was accurate within .0001 and the temporal offset was accurate within 1.12 ms.

When the final temporal scaling factor was identified, the amplitude scaling factor was obtained by computing the square root of the ratio of the variance of the target pattern to the variance of the movement pattern. This amplitude scaling factor was applied to the target wave, and the RMS error was again calculated to derive the residual RMS error. The residual RMS error reflects the accuracy of the underlying motor plan, or GMP. The temporal scaling factor, amplitude scaling factor, and residual RMS error were obtained for each of the experimental trials.

The average (across trials, within subjects) temporal and amplitude scaling factors represent the constant error (CE) in time and amplitude parameterization, respectively. The average residual RMS reflects the accuracy of the GMP. In addition, the average within-subject standard deviation of each of these measures was obtained as a measure of the stability of the GMP and parameter assignment. These measures were labeled variable error (VE). It should be noted that the method used for calculated residual RMS VE in the current study is different from that described by Wulf, Schmidt, and Deubel (1993). The method used in the current study is more sensitive to variations in relative timing and amplitude and is thus deemed a more comprehensive measure of variability of the GMP. Whereas our calculation method will result in lower overall VE measures than the measure described by Wulf et al., these differences would be consistent across both experimental groups.

The dependent variables of residual RMS error (CE and VE), temporal scaling factor (CE and VE), and amplitude scaling factor (CE and VE) were analyzed with separate one-way analyses of variance. The between-subjects factor for each analysis was age group.

**Results**

**Unit Structure**

Figure 2 illustrates the mean correlation between landmarks for the adult and child participants. Visual inspection reveals that the two participant groups appear to exhibit different overall correlations as well as different patterns of correlations.

With the exception of three participants, the group of children exhibited correlational patterns consistent with the interpretation that they used a single GMP for the entire movement sequence. That is, there were no abrupt changes in correlations between contiguous landmarks. For the remaining three children, all correlations observed were very low and exhibited no recognizable pattern across landmarks, suggesting that the GMP structure for these children was either not well developed or included more than two GMPs for each movement. In either case, the unit structure for these participants precluded further analysis with the rescaling technique. Thus, the remaining analyses were conducted using the data from the remaining 17 child participants. Additional discussion of the excluded data will be included in the Discussion section.

For the adult participants, the correlations between landmark A and the remaining landmarks are quite low,
whereas the correlations between contiguous landmarks were higher and all statistically significant ($p < .05$). The correlations between the last landmark and each of the preceding landmarks were quite high, becoming slightly lower as the landmarks became further distant from landmark G. Although this pattern of correlations might be interpreted as indicating that the labioman- dibular movement was generated by two generalized motor programs, one that governed the movements represented by the first landmark (from onset to the time of first peak opening velocity) and a second which governed the remainder of the movement, several factors led us to reject this interpretation.

First, when Young and Schmidt (1991) examined the unit structure of an arm-positioning task, they identified a movement pattern (Type I pattern) that was governed by two GMPs, as evidenced by a sharp drop in correlations between landmarks. However, in their study, the sharp drop was observed at a point in the movement that corresponded with a change in action. That is, in an extension-flexion movement, the change in correlations occurred between landmarks representing the completion of extension and beginning of flexion. If a similar phenomenon was operating in the current study, the expected GMP grouping would be the opening gesture as a separate GMP from the closing gesture for each of the opening-closing gestures, or perhaps the first opening and closing gesture separate from the second opening and closing gesture. In fact, the correlation shift was observed midway through the opening gesture. Thus, the present findings are not consistent with the Type I movement described by Young and Schmidt.

It is more likely that the poor correlations between initial and subsequent landmarks represent “start-up” variability associated with initiating a movement. That is, the motor delays (Heuer, 1988; Heuer, Schmidt, & Ghodsian, 1995) during the initiation of a movement may be more variable than those associated with the remainder of the movement.

Thus, in spite of lack of unambiguous unit structure, we proceeded with the subsequent analyses, recognizing that the effect of analyzing the movement pattern as a single GMP, if more than one GMP were used, would be decreased GMP accuracy and increased variability. As will be seen in the Results, this direction of error would not change the significant differences observed between the two groups.

**GMP Accuracy and Stability**

Table 1 lists the mean constant error (CE) and variable error (VE) for each group and each dependent variable. The adult group showed greater GMP accuracy than the children, as evidenced by lower mean residual RMS CE [$F(1, 183) = 12.46, p < .01$]. However, no significant difference in GMP stability, or VE, was observed ($F = 2.02$) between the two groups.

**Temporal Parameterization Accuracy and Stability**

The adult group exhibited greater temporal parameterization accuracy than the children, as evidenced by temporal scaling factors closer to 1.0 [$F(1, 183) = 138.80, p < .01$]. The children exhibited mean temporal scaling factors greater than 1.0, indicating that the movement traces were expanded along the time dimension to best match the target pattern. In other words, the children consistently produced movements of shorter duration than the target patterns. With regard to temporal parameterization stability, the child participants exhibited significantly larger VE than the adult group [$F(1, 183) = 178.57, p < .01$].

**Amplitude Parameterization Accuracy and Stability**

The adult group exhibited greater amplitude parameterization accuracy than the children, as evidenced by amplitude scaling factors closer to 1.0 [$F(1, 183) = 87.85, p < .01$]. Amplitude scaling factors greater than 1.0 indicate that the participant’s movement trace was expanded along the amplitude dimension to best match the target pattern. That is, the children consistently produced movement patterns that were of smaller amplitude than the target pattern. As with temporal parameterization, the child participants exhibited significantly higher amplitude parameterization VE than the adults [$F(1, 183) = 25.46, p < .01$].

<table>
<thead>
<tr>
<th>Dependent measures</th>
<th>Adult Group</th>
<th>Child Group</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>GMP (Residual RMS Error)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant Error*</td>
<td>153.54</td>
<td>171.067</td>
</tr>
<tr>
<td>Variable Error</td>
<td>58.087</td>
<td>50.686</td>
</tr>
<tr>
<td><strong>Temporal Parameterization (Temporal Scaling Factor)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant Error*</td>
<td>.926</td>
<td>1.319</td>
</tr>
<tr>
<td>Variable Error*</td>
<td>.165</td>
<td>.392</td>
</tr>
<tr>
<td><strong>Amplitude Parameterization (Amplitude Scaling Factor)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant Error*</td>
<td>1.03</td>
<td>1.41</td>
</tr>
<tr>
<td>Variable Error*</td>
<td>.191</td>
<td>.41</td>
</tr>
</tbody>
</table>

* Effect of Group was significant at the .01 level.
Discussion

Our a priori predictions were that children would be less accurate and more variable than adults in the assignment of GMPs and corresponding parameters. As well, we suggested that temporal parameterization would be more disrupted than amplitude because the task demanded changes in absolute duration across trials. In regard to these predictions, the findings of the current study can be summarized as follows: Children exhibited reduced GMP and parameterization accuracy relative to the adults. Children were also more variable than adults, but only with respect to parameterization—their performance was not different from the adults with regard to GMP stability. Finally, children showed equal ability to control temporal and amplitude parameters.

We will first address our findings with respect to those of Smith and Goffman (1998). These researchers found high variability in the normalized movement traces of children during speech production tasks. That is, when gross variations in overall duration and/or amplitude were removed by the normalization procedure, children still exhibited high variability in the underlying movement pattern. The findings of the current study are in contrast to Smith and Goffman in this respect. When variation related to overall duration and amplitude was removed through the scaling process, the children in the current study did not exhibit greater variability of GMP production than the adult group. The most obvious explanation for this difference is that although the analysis techniques used by Smith and Goffman were similar to those in the current study, the experimental task was substantially different. At the least, differences in the task may reflect differing degrees of interaction in the two tasks (see Stathopoulos, 1995) and the fact that the tasks have different functional goals. Also, as indicated in the introduction, Smith and Goffman used a speech task where multiple trials were produced at a consistent rate. The task in the current study used a nonspeech oral movement where participants were asked to produce the movement at several different rates, while the underlying relative timing and amplitude of the target pattern remained constant. It is well documented that perceptually acceptable or “accurate” speech productions can be achieved with surprising variability in articulatory timing and placement (Folkins & Linville, 1983; Hughes & Abbs, 1976). Thus, the participants in the Smith and Goffman study had greater flexibility in meeting the “goal” of the task. In contrast, because accuracy was a continuous variable in the current experiment, there was less flexibility in meeting the visual targets, although flexibility in the form of motor equivalence may have been observed had lip and jaw movements been measured independently.

Smith and Goffman (1998) also found that the underlying movement pattern produced by the children was different from that produced by adults, though both groups produced perceptually acceptable speech samples. Specifically, the children spent a greater amount of time on the beginning portion of the movement, leading the authors to suggest that the children were using a feedback mode of movement control during the beginning of the movement, whereas adults likely used a more afferent movement control strategy throughout the movement production. The unit structure analysis of the present study speaks to these findings. For both adults and children, correlations between contiguous landmarks were lower for landmarks nearer the beginning of the movement, suggesting that movement variability was greater during the initial portion of the movement trace. This finding is consistent with the interpretation of greater use of feedback during initiation of movement, but our findings do not support the notion that children used this movement control strategy to a greater extent than did the adults. In fact, the lower correlations at the beginning of movements produced by the adults compared to the children might suggest the opposite—that adults used feedback to a greater extent. It may be that task unfamiliarity leads to a more feedback-driven control strategy (Ballard et al., 2001). If so, the nonspeech task used in the current experiment was equally unfamiliar to all participants, leading both groups to use feedback, particularly during the initial part of the movement. In contrast, the speech task used by Smith and Goffman (1998) may be more unfamiliar to the child speakers.

It is not possible to compare GMP accuracy reported in the current study to the qualitative perceptual analysis reported by Smith and Goffman (1998), even though the normalized movement traces of Smith and Goffman are similar to the rescaled movement traces in the current study. All of the movement trials in the Smith and Goffman study were categorically classified as accurate or inaccurate, as determined by perceptual adequacy, and only accurate trials were examined. In contrast, as suggested above, accuracy in the current study was a continuous variable and all productions were studied. Future research examining variability in nonspeech tasks where accuracy is defined categorically would provide a more similar performance situation to which the Smith and Goffman results could be compared. For example, in an experiment using a task similar to that described in this paper, “accurate” trials could be identified using a predetermined performance range, with only those trials meeting criteria for accuracy being examined. Alternatively, it would also be possible to examine speech movement traces using the current analysis by developing a movement template derived from the
average of a variety of speakers. Using these or other equated designs will aid in the interpretation of differences in findings between speech and nonspeech tasks.

In summary, the current findings were inconsistent with Smith and Goffman (1998) in the following ways: (a) We failed to find that the underlying movement pattern in children's productions were more variable than the adults. (b) Although both children and adults were observed to control the initial portion of movement pattern differently from the remaining portion of the movement, children were not observed to use this control pattern to a greater extent than did the adults. However, it is possible that several differences between the experimental task used by Smith and Goffman and the task in the current study may account for the discrepant findings.

The present study examined several additional aspects of movement control that were not addressed by Smith and Goffman (1998)—specifically temporal and amplitude parameterization accuracy and stability. We found that children were less accurate and more variable in their assignment of both temporal and amplitude parameters. Specifically, children tended to produce movements of shorter duration and smaller amplitude than the target patterns. One possible explanation is that the children produced movements of smaller amplitude to meet the timing constraints of faster movements, similar to the common finding of reduced amplitudes associated with reduced movement times during speech production (e.g., Kent & Netsell, 1972). Another explanation for children's reduced movement amplitudes was that the relative size of the articulators made the target movement displacements (maximum 15 mm) simply more difficult for children to produce than for the adults. This explanation is consistent with findings reported by Ballard et al. (2001). They found that on a visuomotor tracking task, children exhibited lower gain ratios than adults, reflecting that they did not move the articulators through the full range of the target movement. These authors proposed that the children, as well as adult participants, might have strategically rescaled their movements to meet the timing requirements of the tracking task.

The shorter overall movement durations exhibited by the child participants were not anticipated and are difficult to explain. One explanation related to the one above is that children may have moved quickly in an effort to move farther. An alternative explanation is that smaller movements overall, both with regard to amplitude and duration, may be easier to control (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979), and the children selected this control strategy in an effort to improve overall performance.

The variability in the assignment of amplitude and temporal parameters is also of interest. Increased movement times or amplitudes cannot explain the variability exhibited by the children. As noted earlier, greater variability is typically expected with longer movement durations and greater amplitudes (Kent & Forner, 1980; Smith, Goffman, & Stark, 1995). However, the children in the current study exhibited high variability concurrent with reduced movement times and amplitudes. One explanation might be that the variability reflects strategic allocation of resources to the assignment of the GMP. Previous research has shown that some individuals with impaired motor control systems were able to assign the GMP or the parameters with accuracy and stability, but not both (Clark & Robin, 1998). The children in the current study may have strategically allocated resources to the assignment of the GMP, resulting in reduced accuracy and stability in the parameter assignments.

Variability in the assignment of temporal parameter specifically is perhaps the most easily explained. The only modification in the target pattern from trial to trial was absolute duration. Within the Schmidt (1975) framework, participants should use the same GMP and amplitude parameter for each trial, but modify the temporal parameter across blocks. Thus, it appears that the children were less able to assign a consistent temporal parameter either within or across blocks. Or, as suggested above, children may have strategically allocated planning resources to the GMP rather than to selection and execution of the temporal parameters.

Of particular interest is the variability observed in amplitude parameterization. The current task involved a movement target whose absolute and relative amplitude remained constant across trials. Therefore, participants could theoretically assign the same amplitude parameter on every trial. In fact, adults were highly accurate and stable in assigning the amplitude parameter, whereas children were quite variable. One possibility is that children did not recognize that the target amplitude did not change from trial to trial. Alternatively, the variability in amplitude parameterization may reflect the efforts of the motor planning system to meet a difficult movement goal. Review of raw data revealed that very few children ever produced movement traces of adequate amplitude, lending additional support to the suggestion that the parameterization inaccuracy might be due to the constraints of a smaller articular system and that the amplitude parameterization variability might reflect central attempts to overcome the limitations of the periphery. Schmidt et al. (1979) suggested that time constraints affect amplitude parameterization in that larger neuromuscular forces are required to produce movement amplitudes in short versus longer
movement times. The findings of the current study suggest that the child participants were less able to accurately or consistently modify neuromuscular forces to meet the amplitude targets of the task. This may reflect underlying processing limitations or a strategic allocation of a limited pool of planning resources to the GMP.

Our findings have several implications for understanding motor control within the framework of Schmidt’s (1975) schema theory. First, the finding that children exhibit reduced accuracy across all measures of performance (GMP, temporal parameterization, and amplitude parameterization) suggests that all of these control structures exhibit developmental change. Additional research including a greater age range of children and adults, particularly those in the adolescent range, is necessary to determine the developmental curve for each of the constructs.

The pattern of variability is of particular interest. Children exhibited greater variability relative to the adults with respect to parameter assignment but not to the GMP. The first implication of this finding is that the GMP and each of the parameters are independent control structures. Support for this argument is also provided by the absence of significant correlation between amplitude and temporal amplitude parameterization. However, we need to question why the GMP appears to be assigned with greater stability than the parameters. One intuitive explanation is that although the “shape” of target movements remains largely unchanged over the course of development (e.g., a backhand swing at age 10 is a backhand swing at age 20), the distance between articulators and the efficiency of the neuromuscular system is in constant flux. Thus, it is strategically advantageous to maintain a stable GMP while allowing for flexibility in parameter assignments. Arguably, when the motor system becomes more stable in adulthood, parameter assignment also becomes more stable. Another, although not contrastive, explanation is that the GMP is the most important control structure and is given strategic priority during motor planning. Finally, the GMP can be conceived as a memory trace analogous to a “phonograph record.” In this conceptualization, we could expect the adults’ “records” to be more accurate than those of the children, but we would expect both types of “records” to be very stable, just as “real” phonograph records would be.

We have focused the discussion of findings primarily within the framework of Schmidt’s (1975) schema theory of motor control. It should be noted that other explanations might also account for developmental variability. Specifically, immaturity in the neuromuscular system or the central pathways regulating visuomotor integration would be expected to result in greater performance variability (e.g., Tingley & Alan, 1975). However, it is unclear how a strict neurobiological explanation accounts for the specific pattern of variability observed in the current study. That is, inconsistent or inefficient recruitment of motor units would be expected to affect similarly the execution of relative and absolute timing and amplitude. As the understanding of the underlying neurophysiology of movement continues to develop, it may be easier to distinguish the influences of central versus peripheral factors on movement performance measures.

Before concluding, a final note is provided regarding the performance of the participants whose data traces were not included in the group analyses. It is worth questioning why 3 of the 20 child participants exhibited movement patterns that were markedly different from those of the remaining participants. The 3 participants of interest did not differ in age from the remaining participants and exhibited gross movement accuracy within the same range as the remaining participants. One explanation is that these 3 participants used a different control strategy, such as feedback monitoring rather than open-loop programming, to control the movement. Because the task did not offer on-line visual feedback during movement production, the participants would have had to rely on kinesthetic and proprioceptive feedback, an arguably difficult task. Another explanation is that these participants exhibited such great variability in GMP and parameter assignment that across-trial correlations could not detect the relationships across trials. Additional study of children who exhibit these anomalous movement control strategies may lend additional insight into the development of movement control.

In summary, the current study was conducted to provide additional information about the nature and source of developmental variability in motor control. The findings were interpreted within the framework of the schema model of motor control. Subsequent study of development of oral motor control might include learning different patterns as well as parameters, perturbing the system to see how rapidly variability arises as a result of perturbations, and continuing to apply similar study to the motor control patterns of individuals with motor speech disorders.

Acknowledgments

This work was supported by NIDCD Center Grant No DC00976. The authors wish to acknowledge Martin Milder for developing the experimental software. We express our gratitude to Kirrie Ballard and Gabrielle Wulf for their thoughtful suggestions on earlier versions of this manuscript.
References


Received September 5, 2000
Accepted May 21, 2001

DOI: 10.1044/1092-4388(2001/080)

Contact author: Heather M. Clark, PhD, Appalachian State University, Department of Language, Reading & Exceptionalities, Boone NC 28608.

E-mail: clarkhm@appstate.edu