The Pennsylvania State University

The Graduate School

PLAN REUSE IN MOTOR AND LANGUAGE PRODUCTION

A Thesis in

Psychology

by

Amy L. Lebkuecher

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

December 2019

The thesis of Amy L. Lebkuecher was reviewed and approved* by the following:

Daniel J. Weiss
Professor Psychology and Linguistics
Thesis Advisor

Brad Wyble
Associate Professor of Psychology

Robert Sainburg
Professor of Kinesiology and Neurology

Melvin Mark
Professor of Psychology
Head of the Department of Psychology

*Signatures are on file in the Graduate School

ABSTRACT

The production of a complex sequence of actions requires the use of a hierarchical, abstract plan held in temporary memory. To lessen the cognitive load imposed on temporary memory by planning, individuals tend to reuse recently activated abstract plans and adapt them as needed rather than generate novel plans for each production instance. While this tendency for reuse (i.e., Plan Reuse) has been found in both motor and language production, research on planning in these domains has largely been conducted independently. The current study evaluates parallels in Plan Reuse across domains by comparing participants' production choices on a motor task and a language task. Participants exhibited analogous patterns of Plan Reuse in both the motor and language tasks such that production on the current trial was influenced by recent production history. The results suggest that Plan Reuse may exist as a domain general heuristic for improving planning and production efficiency.

TABLE OF CONTENTS

LIST OF FIGURES

Introduction

In the mid-20th century, Lashley (1951) argued against a prevailing theory that sequential behaviors could be best explained by simple associative chaining (e.g., Washburn, 1916). Rather, on the basis of several lines of reasoning (see Rosenbaum, Cohen, Jax, Weiss, & Van Der Wel, 2007) Lashley proposed that serial actions in behavior arise as a consequence of hierarchical planning. He extended this theory beyond motor actions to include sequences produced in the context of music and language production (see Fitch & Martins, 2014). While his theory gained relatively broad acceptance (though see, for example, Wickelgren, 1969), there has been little research exploring the implications of his claim that the planning for language production bears a deep relationship with planning sequential behaviors for action (see Fitch & Martins, 2014). Consequently, the goal of the current study is to begin to evaluate whether biases found in language production, as described in the Production-Distribution-Comprehension (PDC) framework (MacDonald, 2013), find parallels in action planning.

PDC framework

The PDC framework asserts that the computational demands of language production are non-trivial (MacDonald, 2013, 2015). Language production is constrained by memory limitations and thus speakers are implicitly biased to craft their utterances in a manner that alleviates the cognitive load imposed by planning. These biases influence language production, which in turn influences the distributional properties of the input for learners, and correspondingly impacts ease of comprehension.

The three production biases delineated by the PDC are Easy First, Plan Reuse and Reduce Interference. Easy First is the tendency for speakers to produce easier, more accessible words and phrases earlier in an utterance and in more prominent syntactic positions relative to difficult constructions. This allows the speaker more time to plan difficult components of the utterance. Another bias in the PDC framework is known as Plan Reuse and refers to the tendency for speakers to reuse recently produced or encountered syntactic structures. It is thought to occur because reproducing a recently activated structure is more cognitively efficient relative to generating a new plan. While Easy First and Plan Reuse allow for more efficient retrieval from long term memory, the Reduce Interference bias is posited to stem from a need to lessen cognitive load on working memory. When elements of an utterance are similar on one or more dimensions (e.g., phonological, semantic) they create interference during planning. As a result, speakers tend to plan utterances in a way that reduces interference between elements due to similarity to the extent possible. All three biases operate in parallel to shape language production.

While the PDC is a linguistic framework, MacDonald (2013) argues that there is evidence for analogous constraints (e.g., Plan Reuse) in non-linguistic motor planning. Plan Reuse in this domain can be ascribed to implicit motor learning (MacDonald, 2013). If language is a special case of action planning, then the implicit learning and subsequent observation of Plan Reuse in language should mirror the effects observed in non-linguistic motor planning. The current study investigates parallels in Plan Reuse behavior during motor and language production.

Plan reuse

Both syntactic priming in language production and hysteresis in motor production involve the reuse of recently activated abstract plans (Bock, 1986; Rosenbaum, Cohen, Meulenbroek, & Vaughan, 2006; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). Despite the similar logic underlying syntactic priming and hysteresis, Plan Reuse in motor and language production has been investigated independently. In the following sections, we will briefly review relevant findings in the syntactic priming and hysteresis literatures and discuss the existing commonalities between these two lines of work.

Syntactic priming

Syntactic priming is a speaker's tendency to produce a novel sentence using a recently activated syntactic structure (Bock, 1986). For example, after encountering or producing a sentence with prepositional phrase structure (e.g., *The server brought the food to the customer*) a speaker is more likely to produce similar phrasing relative to double object phrasing (e.g., *The server brought the customer the food*). It is a robust phenomenon that has been observed in production by children (Foltz, Thiele, Kahsnitz, & Stenneken, 2015; Garraffa, Coco, & Branigan, 2015; Huttenlocher, Vasilyeva, & Shimpi, 2004; Kidd, 2012) and even between languages in bilingual speakers (Bernolet, Hartsuiker, & Pickering, 2013; Hartsuiker, Pickering, & Veltkamp, 2004; Schoonbaert, Hartsuiker, & Pickering, 2007). Overall, the literature suggests that syntactic priming involves reactivating an abstract representation of structural features (i.e., syntax) that is dissociable from conceptual components (i.e., lexicon, semantics; Bock, 1986). This abstract representation is a plan for the order of the words and phrases that constitute an utterance. The tendency to reactivate an abstract plan has a parallel in the literature on hysteresis in motor planning.

Hysteresis

Hysteresis is the influence of prior history on the current state of a system. Its effects have been observed in multiple domains of human behavior and perception including motor planning. In a landmark study of oscillatory patterns in rhythmic finger movement, Kelso (1981) discovered that participants' index fingers spontaneously changed from an anti-phase to an in-phase pattern when a metronome beat increased to a critical speed, but that the in-phase pattern persisted when the metronome beat was lowered below the critical value. These observations led to the development of the Haken-Kelso-Bunz model of self-organization (Haken, Kelso, & Bunz, 1985), a dynamical systems framework that theorized about the influence of prior movement on current movement, though without recourse to cognition or memory. Subsequent studies inspired by this framework found converging evidence for hysteresis in the motor planning (Rostoft, Sigmundsson, Whiting, & Ingvaldsen, 2002; Sørenson, Ingvaldsen, & Whiting, 2001).

While dynamical systems approaches may accurately characterize hysteresis effects, it has been argued that they fail to adequately account for the degrees-of-freedom problem in motor planning (Rosenbaum & Jorgensen, 1992). Action execution can often take many possible forms (i.e., has many degrees of freedom; Bernstein, 1967), yet production is often uniform, suggesting that constraints operate to limit the number of action plans considered and increase planning efficiency. Arguably, constraints on motor planning promote efficient execution. Cognitive models of motor planning, such as the posture-based motion planning theory (Rosenbaum, Cohen, Meulenbroek, & Vaughan, 2006; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001), suggest that these constraints arise because individuals must quickly decide between competing alternative plans stored in memory during action production (Wolpert & Landy, 2012). This theory proposes that goal postures used to complete actions are first selected from memory and then adapted to suit the demands of the current environment. Operating within this framework, hysteresis is the selection of a recently activated goal posture.

A number of object manipulation studies provided an interpretation of hysteresis effects congruent with the posture-based motion planning theory (Cohen & Rosenbaum, 2004;

Rosenbaum et al., 2006, 2001; Rosenbaum & Jorgensen, 1992). In these experiments, participants were more likely to persist using the same grasp when completing a task with objects on consecutive trials rather than adopting a new grasp. The authors argued that participants selected a recently used posture (i.e., grasp) from memory and “tweaked” it for more efficient production on the current trial.

In addition to object manipulation studies, findings from an experiment that evaluated motor planning and memory in parallel provided particularly compelling evidence for a cognitive theory of motor planning. When concurrently completing a memorization and a motor task (Weigelt, Rosenbaum, Huelshorst, & Schack, 2009), participants exhibited a higher probability of engaging in hysteresis when memory demands were low. This pattern suggests a trade-off between memory and motor planning such that individuals produce action plans less efficiently when high demands are placed on their memory. This trade-off is consistent with both posture-based motion planning theory and the PDC framework, since both accounts argue that production is constrained to be more efficient by memory limitations in action and language respectively. Plan Reuse leads to more efficient production since reactivating and adapting an existing plan is less cognitively demanding than generating an entirely novel plan (MacDonald, 2013; Rosenbaum et al., 2006, 2001; Smith & Wheeldon, 2001).

Computational efficiency

If reusing abstract plans is a more efficient production strategy than generating new ones, it should be faster to initiate production with a reused action plan than a novel one. Consistent with this proposition, there is evidence for the computational efficiency of Plan Reuse in research on syntactic priming and hysteresis in motor planning. Speakers exhibit decreased response times (RT) when producing sentences with primed relative to novel syntactic structures

(Smith & Wheeldon, 2001). In the motor domain, individuals' RT is decreased when reaching for a target with the same hand as the previous trial relative to using a different hand (Valyear, Fitzpatrick, & Dundon, 2018). The decreased RT on trials with syntactic priming and hysteresis in language and motor production experiments reflects the computational efficiency of Plan Reuse as it allows for faster successful execution of an action plan. Taken together, the literature on syntactic priming in language production and hysteresis in motor planning suggest that there is converging evidence across disciplines for Plan Reuse as a domain general cognitive heuristic that results in more efficient plans of action.

Current study

With this similarity in mind, our study presented subjects with a motor and a language task that afforded opportunities for Plan Reuse. The motor task was adapted from a study that investigated hysteresis in the reaching behaviors of cotton-top tamarin monkeys (*Saguinus oedipus*; Weiss & Wark, 2009). In that experiment, tamarins reached through a hole in a sheet of Plexiglas to retrieve marshmallows placed at one of 11 fixed locations in an arc of equidistant points around the aperture. Each trial, the position of the marshmallow was incremented such that across trials, the marshmallow progressed in either a clockwise or counterclockwise arc from the perspective of the subject. The tamarins tended to persist with using their initial hand for positions past the midline in both directions before switching. For example, in a clockwise progression, the tamarins reached through the aperture with their right hand for the extreme angle positions, and then persisted to use their right hand even past the midline. By comparing the position where individuals switched hand use (i.e., the transition point) when completing the task clockwise versus counterclockwise, it was possible to obtain a hysteresis area, an area where they were more likely to switch hands (see Rostoft et al., 2002).

In the current study, we modified this task for human adults. Instead of retrieving marshmallows through a Plexiglas aperture, participants reached through a metal hoop aperture to touch dots as they appeared on a touchscreen. Similar to the paradigm in Weiss and Wark (2009), 11 targets were spaced equidistantly at fixed locations in arc configuration. The targets appeared one at a time, progressing incrementally clockwise or counterclockwise from the perspective of the participant. In congruence with the findings of the tamarin study, we anticipated that participants' transition point would be farther to the right when the arc progressed clockwise and farther to the left when the arc progressed counterclockwise.

For the language task, we modified an experimental paradigm designed to evaluate Heavy Noun Phrase Shift (HNPS; Stallings, MacDonald, & O'Seaghdha, 1998). HNPS is the tendency for speakers to produce long or "heavy" noun phrase direct objects at the end of a sentence rather than immediately following the verb (Stallings et al., 1998; Wasow & Arnold, 2003). For example, in utterances that consist of a verb phrase, a noun phrase (NP) and a prepositional phrase (PP), English speakers tend to prefer to place the NP before the PP (e.g., *I explained the plans to Michael*) even though the alternative (e.g., *I explained to Michael the plans*) is also acceptable. However, once the NP becomes heavy, speakers become more likely to produce the form with the PP first (as in *I explained to Michael the extravagant plans for the new amusement park near the interstate*).

HNPS is thought to occur as a result of the Easy First bias described in the PDC framework (MacDonald, 2013). As the NP becomes heavier (i.e., more difficult to plan for production) relative to the PP, the latter is moved to the beginning of the predicate in the utterance plan. While there are a variety of factors that contribute to a NP becoming heavy (e.g., conceptual accessibility of the words in the NP), there is evidence that the propensity for HNPS in the production of English utterances increases with the length of the NP in words. This pattern has been attested with both corpus and psycholinguistic methods (Stallings et al., 1998; Wasow & Arnold, 2003).

In this experiment, we created an HNPS task in which the NP weight was incremented. This was meant to serve as an analogue to the motor task in which the dot progressed incrementally from one side to another. That is, we were interested in determining whether the point at which the sentence structure changed could be influenced by prior utterances in much the same way that the point at which subjects switched hands could be influenced by prior reaches. As the NP of an utterance increases in weight, the probability that a speaker will choose PP first phrasing (e.g., *I explained to Michael the plans*) over the canonical NP first phrasing (e.g., *I explained the plans to Michael*) should increase. Evidence from linguistic corpus data suggests that speakers are more likely to shift NP direct objects to the end of an utterance when the length or "weight" of the NP exceeds the other material in the verb phrase (in this case a PP) by four or more words (Hawkins, 1994).

The relationship between NP weight and HNPS was further explored by Stallings and colleagues (1998) using a series of sentence construction experiments. In one experiment, participants were presented with three phrases on a computer screen for each trial: a subject-verb phrase (two to three words long), a two-word PP, and a short (two-word) or long (10-word) NP. Participants produced sentences using the three phrases on the screen. They were significantly more likely to produce the PP before the NP when the NP was long relative to when it was short. This methodology provided the foundation for our language task.

In the current study, we employed a modified version of the paradigm used in experiment two of Stallings et al. (1998). We adjusted the materials and procedure so that participants would be presented with NPs that increased or decreased in length by one word on consecutive trials. Given the possibility of a critical value for HNPS, evaluating this effect using an incremental procedure might allow for the discovery of a “hysteresis area” for this linguistic phenomenon. Identifying the hysteresis area for both a motor and language production task could yield valuable evidence for understanding whether Plan Reuse operates similarly across different domains.

As a secondary hypothesis, we propose that Plan Reuse will vary as a function of preference (i.e., preferred plans may be more likely to be reused). In the motor task, it is probable that participants will show a preference for using their dominant hand relative to their non-dominant one (Rostoft et al., 2002; Valyear et al., 2018). On the language task, we expect English speakers to exhibit a default preference for producing NP first structure based on the findings from previous work on HNPS (Stallings et al., 1998; Wasow & Arnold, 2003). By considering the role of preference in Plan Reuse, the current study aims to not only evaluate hysteresis effects in motor and language planning, but also to qualify which plans might be more or less susceptible to reuse. Parallel hysteresis effects would suggest that Plan Reuse may operate in both domains to reduce the memory demand on production, as suggested by MacDonald (2013).

Methods

Participants

Participants were 205 undergraduate students recruited from participant pools at Penn State University and University of Wisconsin-Madison. We excluded subjects who were non-native speakers of English (N = 7) or not right hand dominant (N = 42). This left us with a final sample of 156 participants (23 males and 125 females) whose average age was 18.82 years (SD =

1.08). Participants were classified as non-right-hand dominant if their laterality quotient on the Edinburgh Abbreviated Handedness Inventory was less than 61 (Veale, 2014).

Motor task

Materials

The motor task was completed on a Dell Optiplex 9020 desktop computer with a 23-inch touchscreen monitor laid flat on its back. The task was run using PsychoPy version 1.8.3.4 software. The aperture for participants to reach through during the task was constructed of pliable metal and wood with a hoop portion approximately six inches in diameter. Participants were also provided an office chair with adjustable height to sit in during the task. Videos of participants' performance during the task were recorded with a Panasonic HC-V700M video camera.

Stimuli

16 blue dots (5 for practice trials and 11 for the main task) 50 pixels each in diameter appeared on the touchscreen one a time. Dots for practice trials appeared in 5 fixed locations: 0, -36, 36, -90 and 90 degrees relative to the midline. Negative values indicate a location to the left of the midline while positives indicate a location to the right. The 11 dots for the main task appeared one at a time in arc at -90, -72, -54, -36, -18, 0, 18, 36, 54, 72 and 90 degrees relative to the midline (see Figure 1). The main task progressed through the arc one position at a time clockwise or counterclockwise.

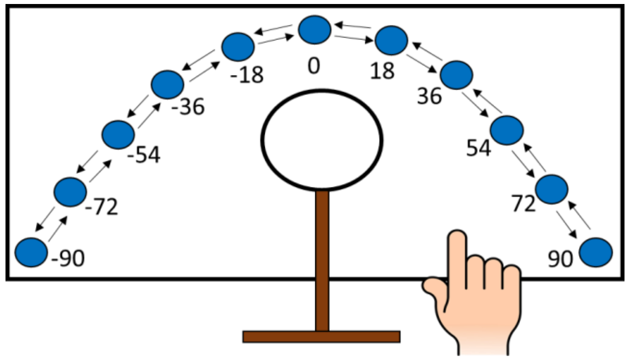

Figure 1. A diagram illustrating the full arc of targets for the motor task. The target dots only ever appeared one at a time. The arrows and numbers were also never displayed to participants but are only present to illustrate the position of the target and directions of the two arc progressions. Rather than parallel to the touchscreen as shown, the hoop aperture was positioned perpendicular to the touchscreen with the flat base on the desk and the hoop portion on top.

Task

Before beginning the task, the experimenter instructed participants to adjust the chair height to their comfort level. The experimenter verified the adequacy of the chair height by asking the participant to reach through the hoop aperture and touch all four corners of the touchscreen monitor. Participants were then instructed (both by the experimenter and via on-screen text) to hold down the “F” and “J” keys with their left and right index finger respectively until a dot appeared on the screen. They were informed that the task would involve reaching through the hoop with one hand to touch dots as they appeared on the screen while continuing to press down on the appropriate key with their other hand. The experimenter made it clear to participants that they should feel free to use either hand to complete the task.

Before test, there were five practice trials where dots appeared at fixed points on the screen as described in the previous section. The practice trials were designed to familiarize participants with the task and encourage the use of both hands. The main part of the motor task consisted of four arcs of 11 dots appearing as described in the previous section. Participants first completed two arcs in succession. The first arc followed either the clockwise or counterclockwise progression with the order counterbalanced across participants. During the second arc, participants completed the progression opposite the one completed in the first arc. The motor task was repeated at the end of the experimental session (after a number of intervening tasks). For the third and fourth arcs, the order of dots appearing (clockwise or counterclockwise) was reversed (e.g., if the participant initially completed the task going first clockwise and then counterclockwise, the second task started counterclockwise). All trials were video recorded to ensure accurate data coding.

Language task

Materials

Participants completed the task on a Dell Optiplex 9020 desktop computer with a standard 24-inch widescreen monitor. The task was run using PsychoPy version 1.8.3.4 software. Audio of the participants' performance was recorded with a Blue© Snowball iCE microphone.

Stimuli

Each display consisted of three phrases total with one phrase at the top, center and bottom of the display (see Figure 2). The initial verb phrase (e.g., "I explained") was always in the center in red while the NP and PP were displayed at the top and bottom of the screen (location counterbalanced across trials). These displays were generated pseudorandomly for each trial. The initial verb phrase always had the subject "I" paired with one of 11 possible verbs. The PP always consisted of one of 21 possible phrases beginning with "to" and ending in a person's name. There were 242 possible NPs that ranged in length from two (e.g., "the answers") to twelve words (e.g., "the answers to last week's challenging twenty point quiz on English Literature"). Each participant only viewed 21 of the 242 possible NPs. 242 possible NPs were generated to provide a wide variety of stimuli within and between subjects. This variety ensured that effects due to differences in the length of the NP did not occur as a result of any particular

NPs. A subset of 21 phrases was selected to allow participants to complete one or two trials for each NP weight (two to twelve words in length). The logic of the 21 trials is explained in greater detail in the next section.

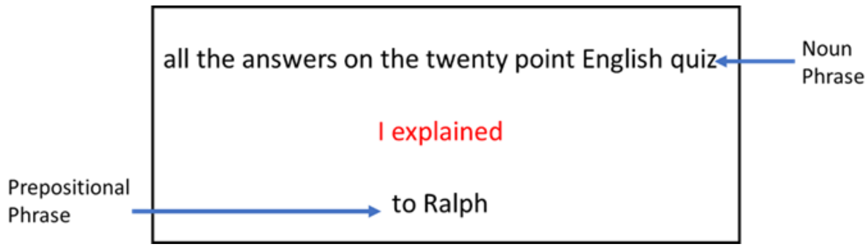

Figure 2. A sample of the display viewed on a computer screen by participants during the language task. The arrows and labels "noun phrase" and "prepositional phrase" were not shown to participants but are included here for explanation of the stimuli.

Task

Participants were instructed to create sentences out loud using all phrases on the screen, always starting with the phrase in the center and ending with both of the other phrases in whatever order they preferred. They were presented with 21 trials in ascending and descending order. Ascending trials began with a stimulus screen that had a two-word NP which was subsequently increased by one word per trial until reaching a maximum length of 12 words. Descending trials began with a twelve-word NP and decreased by one word per trial until reaching a minimum length of two words.

All participants completed both ascending and descending trials, but some participants began with ascending trials while others began with descending trials. Every participant regardless of condition completed two trials for NPs ranging from three to 11 words. Participants who completed the ascending trials first also completed two trials of two-word NPs, but only one trial with a 12-word NP. Those who completed the descending trials first completed two trials with 12-word NPs, but only one trial with a two-word noun phrase. Due to the incrementally increasing and decreasing nature of the task, these adjustments were made by condition to ensure that no two adjacent trials had the same NP weight. The task was self-paced, and participants pressed the space bar to initiate each trial. All responses were audio recorded for data coding purposes.

Questionnaires

Paper and pencil versions of the Language History Questionnaire (LHQ; Li, Sepanski, & Zhao, 2006) and the Edinburgh Handedness Inventory Short Form (Veale, 2014) were used to assess a participants' language background and handedness respectively. The LHQ asked participants questions about their demographic information, native language, experience with other languages, and speaking, listening, reading and writing proficiency in each language. The handedness inventory asked participants to rate how often they used their right versus left hand for writing, brushing their teeth, throwing, and using a spoon. For each item they could select: always right (100), sometimes right (50), both equally (0), sometimes left (-50) or always left (-100). Their scores for the four items were added up and divided by four to calculate each participant's laterality quotient. Individuals with a laterality quotient of less than -60 are considered left hand dominant while those with a quotient ranging from -60 to 60 have mixed hand dominance. Right handed individuals have a laterality quotient greater than 60.

Participants were also asked to report the amount of effort that they used when completing the tasks in the experiment on a scale from 1 "least effort" to 10 "most effort". Effort was defined as how hard they tried rather than how well they did or how difficult they found the tasks. Overall, participants scored relatively high in their effort rating ($M = 8.45$, $SD = 1.44$), so we did not include the effort rating in our analyses.

Procedure

Participants provided written consent before beginning the experiment. All testing was completed in a soundproof chamber. The experiment began with the first two arcs of the motor task. Then, participants completed two paper mazes. After that they completed the language task. Following the language task, participants completed two three-dimensional mazes, the second two arcs of the motor task, two additional paper mazes, the Operation Span (OSPAN; Unsworth, Heitz, Schrock, & Engle, 2005) task, and two additional three-dimensional mazes. Additionally, some of the participants from the University of Wisconsin-Madison completed a walking version of the three-dimensional maze. The mazes were adapted from those utilized by Christenfeld (1995). After completing the battery of tasks, participants filled out the LHQ and Edinburgh Handedness Inventory Short Form. The motor and language tasks in this experiment were completed as part of a larger battery of tasks that assessed motor and language production as well as executive function. The other tasks in this battery are beyond the scope of this experiment and will be discussed in other manuscripts.

Results

Motor

All analyses were conducted using R version 3.6.1. For the motor analyses we excluded subjects who did not switch hand use during at least one arc on the reaching task ($N = 13$). To evaluate the presence of a hysteresis effect in participants' performance on the motor task, we conducted a linear mixed effects model with transition point (the position where an individual switched hand use during an arc) as the outcome variable, the direction of the arc (clockwise or counterclockwise) as a within-subjects fixed effect, and the participant's condition (whether they completed the clockwise or counterclockwise progression first) as a between-subjects fixed effect. We also included the interaction between direction and condition as a fixed effect. For random effects, we added a random intercept for each participant and a by-participant random slope for direction to the model.

We observed a significant main effect of direction on participants' transition point (β = -1.93, t = -19.09, p < .001), but no main effect of condition (β = -.05, t = -.60, p = .55) nor significant interaction between condition and direction (β = .00, t = -.01, p = .99). Figure 3 illustrates the difference in transition point in the clockwise and counterclockwise arc progressions. In order to investigate how hand preference influenced hysteresis in the motor task, we conducted an additional linear mixed effects model with the distance between the midline (position 6) and the transition point as the outcome variable and direction as a fixed effect. We also included a random intercept for each participant and random by-participant slope for direction. The model confirmed that a participant's transition point when completing the clockwise arc progression (M = 1.17) was significantly further shifted from the midline than when completing the counterclockwise progression (M = .81, β = -.36, t = -4.03, p < .001) suggesting that there is a larger hysteresis effect when participants begin the motor task with their dominant hand.

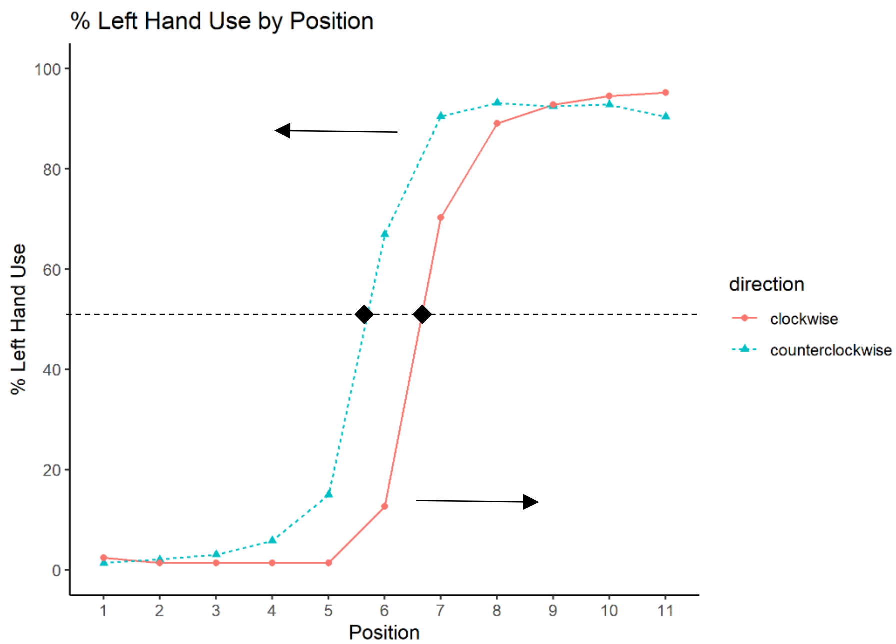

Figure 3. Percentage of left hand use at each position on the motor task separated by direction. The pink line illustrates left hand use in the clockwise progression while the blue line illustrates left hand use in the counterclockwise progression. Arrows indicate the order of the positions participants completed in each direction (starting with position one going clockwise and position 11 going counterclockwise). The dotted line represents the point where left hand use is at 50% and the black diamonds represent the mean transition point of each progression.

Language

In order to verify that the within and between-subject manipulations produced the expected influence on phrasing choice, we conducted a generalized linear mixed effects model with phrasing choice on the current trial (0 = NP first, 1 = PP first) as the outcome variable and trial type (ascending vs. descending) as a within-subjects fixed effect, participant condition (ascending trials first vs. descending trials first) as a between-subjects fixed effect, and an interaction between trial type and condition as a fixed effect. We also included the fullest random effects structure that allowed the model to converge: a random by-participant slope for trial type and a random by-item slope for the interaction between trial type and condition. There was a significant effect of trial type (β = .19, z = 2.34, p = .02) and condition (β = .30, z = 4.04, $p <$ .001), but only a marginal interaction between condition and trial type (β = .31, z = 1.82, p = .07). Participants were more likely to produce PP first phrasing on a given trial in the descending first condition and on descending trials.

Despite the marginal interaction between condition and trial type, there appears to be more of a difference in the proportion of PP first phrasing for ascending relative to descending trials in the descending first condition, than the ascending first condition (as illustrated in Figure 4). Although our analyses revealed a main effect of trial type, we wanted to determine whether the influence of trial type on current phrasing was primarily driven by the performance of participants in descending first condition. To address this, we conducted generalized linear mixed effects models for each condition separately with phrasing choice on the current trial as the outcome variable and trial type as a fixed effect. Additionally, we included a random by-participant slope for trial type and a random by-item slope for trial type as random effects. The models confirmed that participants in the ascending first condition were not more likely to produce PP first phrasing on descending compared to ascending trials (β = .05, z = .25, p = .80). Conversely, participants in the descending first condition were more likely to produce PP first phrasing on descending relative to ascending trials (β = .37, z = 2.07, p = .04).

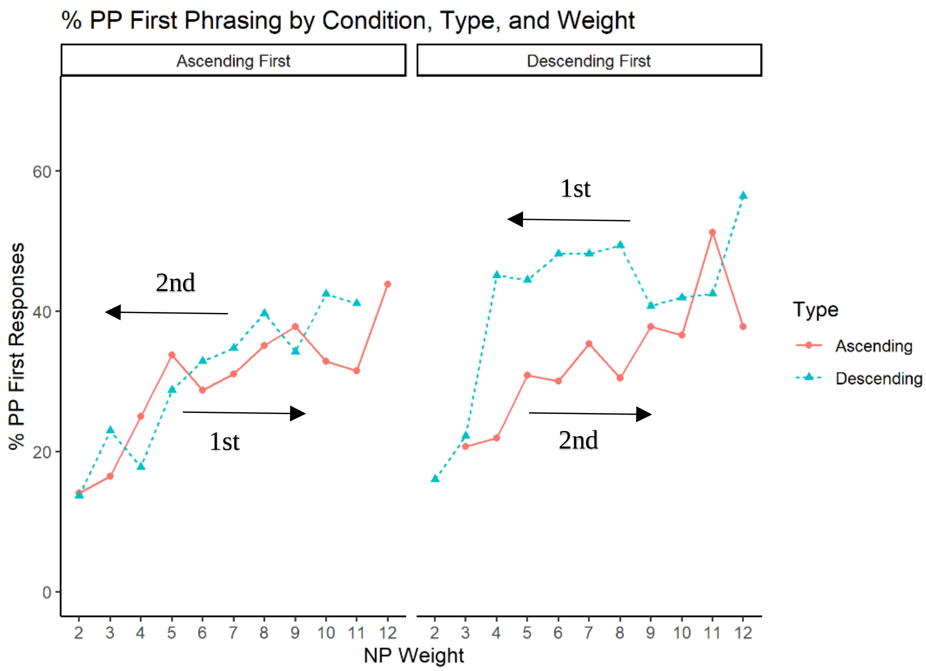

Figure 4. Percentage of prepositional first phrasing at each noun phrase weight on the language task separated by condition. Ascending trials are represented in pink and descending are represented in blue. Arrows indicate the order of the noun phrase weights participants completed in each trial type (starting with weight two on ascending trials and weight 12 on descending trials).

Discussion

In order to evaluate the possibility that planning for language production and motor actions are subject to similar biases, we conducted a production task in each domain. Our motor task was based on prior research studying hysteresis in nonhuman primates (Weiss & Wark, 2009). Participants reached through an aperture to touch targets appearing on a touchscreen. The targets progressed each trial incrementally in an arc, either clockwise or counterclockwise. We predicted that participants would persist in their hand choice in both directions, though showing a stronger effect in the direction that began with a dominant hand reach. In line with these predictions, participants switched hand use past the midline target for both arc progressions with the switch point even farther from the midline in the clockwise progression. For the language task, participants constructed sentences aloud using three phrases presented visually on a computer screen. Similar to the position of the target in the motor task, the weight of the NP incremented on each trial, either increasing or decreasing by one word.

We hypothesized that participants' production choice on a given trial (NP first or PP first) would be influenced by their recent production history. As predicted, participants demonstrated a higher probability of producing PP first phrasing when beginning the language task with heavier noun phrase weights (i.e., the descending first condition). When investigating the effect of trial type in each condition separately, it was revealed that participants were more likely to produce PP first phrasing on descending relative to ascending trials in the descending first condition only.

A possible explanation for this difference between the conditions could be the strong preference that English speakers exhibit for NP first phrasing (Hawkins, 1994). Participants in the ascending first condition exhibited a lower proportion of PP first phrasing overall, and no significant difference in production of PP first phrasing on ascending relative to descending trials, perhaps due to beginning the task with a higher probability of producing the preferred NP first phrasing. Thus, it may only be possible to observe a significant Plan Reuse effect for PP first phrasing when speakers are initially primed to produce the less preferred structure. Consistent with our hypotheses, we found evidence for Plan Reuse behaviors in both tasks and higher levels of Plan Reuse for preferred plans (i.e., right hand or NP first phrasing) relative to less preferred plans (i.e., left hand or PP first phrasing).

The findings of the current study suggest that there are parallels in Plan Reuse across the motor and language domains. On the motor task, individuals exhibited explicit transition points in each arc where they switched hand use. These transition points differed by the direction of the arc progression. The difference between these transition points delineated a hysteresis area of uncertainty in hand use (Rostoft et al., 2002; Weiss & Wark, 2009). There was also evidence for an analogous hysteresis effect on phrasing choice. As evidenced by the differing levels of Plan Reuse for PP first phrasing across condition and trial type, individuals' Plan Reuse was modulated by experimental factors. If the production of syntactic structure on the current trial depended only on NP weight (Hawkins, 1994; Stallings, MacDonald, & O'Seaghdha, 1998), then we would not expect to see differences based on participants' condition or trial type. Although we do see PP first phrasing increase with NP weight, participants that began with descending trials exhibited more persistence in their PP first phrasing relative to participants that began with ascending trials.

Based on the findings from the language task, we propose that a hysteresis area exists for language production, but that it may manifest differently in the language and motor tasks due to differences in the task demands as well as the output being more uniform in the motor task (i.e., there was only a single switch point). This is the first study (to our knowledge) that has tried to apply the structure of the hysteresis experiments in the motor domain to study language production choices. While the tasks and results differ across domains, it is interesting to note that there does seem to a be a hysteresis area. That is, participants are more likely to produce PP first phrasing for the same noun phrase weight on descending trials than ascending trials when beginning with descending trials first (see Figure 4). The noun phrase weights with a large disparity in the production of PP first phrasing on ascending relative to descending trials signify a hysteresis area where production choice is more ambivalent and vulnerable to the influence of recent production history.

In addition to recent production history, there is a need to consider Plan Reuse over the course of an individual's life experience. Since the individuals included in our sample were classified as right-handed based on their self-reported, strong preference for right hand use in manual motor tasks (i.e., writing, using a spoon; see Veale, 2014), it is likely that they have a long-term history of using their right hand more than their left for these actions. Similarly, given that only native English speakers qualified as participants, it is probable that they produced far more utterances with a NP preceding a PP relative to placing the PP first (Hawkins, 1994; Stallings et al., 1998; Wasow & Arnold, 2003). This preference for NP first structure is consistent with an account of Plan Reuse in language as the long-term, implicit learning of syntactic structures (MacDonald, 2013). Consequently, the exaggerated hysteresis exhibited by participants during right hand use could result from long-term implicit motor learning. However, both cognitive and dynamical systems accounts of hysteresis have typically focused on the effect of recent production history on current production (Haken et al., 1985; Rosenbaum et al., 2001). While further research is needed to investigate alternative explanations, the current study may illustrate a potential influence of long-term Plan Reuse on current motor production analogous to the long-term implicit learning of syntactic structures observed in language.

Despite these parallels, the effect of within and between-subject conditions differed by domain. The within-subject condition (i.e., direction of progression) affected Plan Reuse behavior on the motor task, while the between-subject condition (i.e., which trial type was completed first) was more influential for Plan Reuse in the language task. The within-subject condition in the language task (i.e., ascending vs. descending trial type) was only significant for participants in the descending first condition when analyzing the effect of trial type for each between-subjects condition separately. The difference could be idiosyncratic to the specific tasks utilized in the current study. The language task was more complex than the motor task in terms of the variables that differed between trials. For the motor task, the attributes of the target itself (i.e., size, shape, color) remained constant. The only variables that differed from trial to trial were the position of the target in the arc configuration and the direction of the progression.

Conversely, the language task varied across trials not only by NP weight and trial type, but also in the words that composed the phrases as well as the position of the NP and PP on the computer screen. Additionally, the structure of the motor task led participants to switch hand use only once whereas the language task led to multiple switches. These task differences may have contributed to divergent influences of within and between-subject factors on the motor and language tasks.

The simplified structure of the motor task may have also led to a lower level of individual variability in production relative to the language task. The existence of defined transition points on the motor task, and lack thereof in the language task, suggest that production was more uniform in the motor task. If Plan Reuse draws from a common substrate across motor and language planning, then we might expect the level of Plan Reuse in motor production to correlate with Plan Reuse in language production. The low variability in performance on the motor task makes it difficult to examine this relationship. Future studies that utilize more complex motor tasks which allow for more than one transition point in hand use (e.g., Valyear, Fitzpatrick, & Dundon, 2018) may lead to greater variability in behavior that would be beneficial for comparisons with language production. Alternatively, individuals may vary in their RT as a factor of Plan Reuse even if their response choices are relatively uniform. To explore this possibility, we will conduct additional analyses involving RT for both tasks to demonstrate that Plan Reuse is a cognitive heuristic that results in more efficient production. Further, RT may provide a better variable for analyzing individual differences across tasks.

Conclusions

The current study explored commonalities in Plan Reuse across motor and language production. Although there are some clear differences, our findings revealed some intriguing parallels underlying Plan Reuse in both domains. Participants exhibited an influence of recent production history on planning in both motor and language tasks. Additionally, their long-term production history may have exerted an influence on current production choices as evidenced by their protracted reuse of preferred production plans. In addition to further exploring these parallels in Plan Reuse across domain, future research should investigate other biases found in the PDC such as Easy First and Reduce Interference (MacDonald, 2013).

REFERENCES

Bernolet, S., Hartsuiker, R. J., & Pickering, M. J. (2013). From language-specific to shared syntactic representations: The influence of second language proficiency on syntactic sharing in bilinguals. *Cognition, 127*(3), 287–306. https://doi.org/10.1016/j.cognition.2013.02.005

Bernstein, N. A. (1967). *The coordination and regulation of movements*. London: Pergamon Press.

Bock, J. Kathryn. (1986). Syntactic persistence in language production. *Cognitive Psychology*, *18*(3), 355–387. https://doi.org/10.1016/0010-0285(86)90004-6

Bock, J K. (1986). Syntactic persistence in language production. *Cognitive Psychology*, *18*(3), 355–387. https://doi.org/10.1016/0010-0285(86)90004-6

Christenfeld, N. (1995). Choices from identical options. *Psychological Science*, *6*(January), 50–55. https://doi.org/10.1111/j.1467-9280.1995.tb00304.x

Cohen, R. G., & Rosenbaum, D. A. (2004). Where grasps are made reveals how grasps are planned: generation and recall of motor plans. *Experimental Brain Research*, *157*, 486–495. https://doi.org/10.1007/s00221-004-1862-9

Fitch, W. T., & Martins, M. D. (2014). Hierarchical processing in music, language, and action: Lashley revisited. *Annals of the New York Academy of Sciences*, *1316*(1), 87–104. https://doi.org/10.1111/nyas.12406

Foltz, A., Thiele, K., Kahsnitz, D., & Stenneken, P. (2015). Children's syntactic-priming magnitude : lexical factors and participant characteristics *. *Journal of Child Language, 42*, 932–945.

Garraffa, M., Coco, M. I., & Branigan, H. P. (2015). Effects of Immediate and Cumulative Syntactic Experience in Language Impairment: Evidence from Priming of Subject Relatives in Children with SLI. *Language Learning and Development*, *11*(1), 18–40. https://doi.org/10.1080/15475441.2013.876277

Haken, H., Kelso, J. A. S., & Bunz, H. (1985). *A Theoretical Model of Phase Transitions in Human Hand Movements*. *Biol. Cybern* (Vol. 51). Retrieved from https://link.springer.com/content/pdf/10.1007/BF00336922.pdf

Hartsuiker, R. J., Pickering, M. J., & Veltkamp, E. (2004). Is syntax separate or shared between languages? Cross-linguistic syntactic priming in Spanish-English bilinguals. *Psychological Science*, *15*(6), 409–414. https://doi.org/10.1111/j.0956-7976.2004.00693.x

Hawkins, J. A. (1994). *A performance theory oforder and constituency.* Cambridge, UK: Cambridge University Press.

Huttenlocher, J., Vasilyeva, M., & Shimpi, P. (2004). Syntactic priming in young children. *Journal of Memory and Language*, *50*(2), 182–195. https://doi.org/10.1016/j.jml.2003.09.003

Kelso, J. A. S. (1981). On the oscillatory basis of movement. *Bulletin of the Psychonomic Society*, *18*, 63.

Kidd, E. (2012). Implicit statistical learning is directly associated with the acquisition of syntax. *Developmental Psychology*, *48*(1), 171–184. https://doi.org/10.1037/a0025405

Lashley, K. (1951). The problem of serial order in behavior. In L. A. Jeffress (Ed.), *Cerebral mechanisms in behavior; the Hixon Symposium.* (pp. 112–146). Oxford: Wiley.

https://doi.org/10.1093/rfs/hhq153

Li, P., Sepanski, S., & Zhao, X. (2006). Language history questionnaire: A Web-based interface for bilingual research. *Behavior Research Methods*, *38*(2), 202–210. Retrieved from https://link.springer.com/content/pdf/10.3758/BF03192770.pdf

MacDonald, M. C. (2013). How language production shapes language form and comprehension. *Frontiers in Psychology*, *4*(April), 1–16. https://doi.org/10.3389/fpsyg.2013.00226

MacDonald, M. C. (2015). The emergence of language. In B. Macwhinney & W. O'Grady (Eds.), *Handbook of Language Emergence* (pp. 81–98). Hoboken: John Wiley & Sons. https://doi.org/10.1111/mila.12160

Rosenbaum, D. A., Cohen, R. G., Jax, S. A., Weiss, D. J., & Van Der Wel, R. (2007). The problem of serial order in behavior: Lashley's legacy. https://doi.org/10.1016/j.humov.2007.04.001

Rosenbaum, D. A., Cohen, R. G., Meulenbroek, R. G. J., & Vaughan, J. (2006). Plans for Grasping Objects. In M. Latash & F. Lestienne (Eds.), *Motor control and learning over the lifespan* (pp. 9–25). New York: Springer. Retrieved from http://informatiksysteme.pt-it.de/mti-2/cd-rom/index.html

Rosenbaum, D. A., & Jorgensen, M. J. (1992). Planning macroscopic aspects of manual control *. *Human Movement Science, 11*, 61–69.

Rosenbaum, D. A., Meulenbroek, R., Vaughan, J., & Jansen, C. (2001). Posture-based motion planning: Applications to grasping. *Psychological Review*, *108*(4), 709–734. https://doi.org/10.1037/0033-295X.108.4.709

Rostoft, M. S., Sigmundsson, H., Whiting, H. T. A., & Ingvaldsen, R. P. (2002). Dynamics of hand preference in 4 year-old children. *Behavioural Brain Research*, *132*(1), 59–68. https://doi.org/10.1016/S0166-4328(01)00415-6

Schoonbaert, S., Hartsuiker, R. J., & Pickering, M. J. (2007). The representation of lexical and syntactic information in bilinguals: Evidence from syntactic priming. *Journal of Memory and Language*, *56*(2), 153–171. https://doi.org/10.1016/j.jml.2006.10.002

Smith, M., & Wheeldon, L. (2001). Syntactic priming in spoken sentence production - an online study. *Cognition*, *78*, 123–164. Retrieved from www.elsevier.com/locate/cognit

Sørenson, V., Ingvaldsen, R. P., & Whiting, H. T. A. (2001). The application of co-ordination dynamics to the analysis of discrete movements using table-tennis as a paradigm skill. *Biological Cybernetics, 85,* 27–38. Retrieved from https://link.springer.com/content/pdf/10.1007/PL00007994.pdf

Stallings, L. M., MacDonald, M. C., & O'Seaghdha, P. G. (1998). Phrasal Ordering Constraints in Sentence Production: Phrase Length and Verb Disposition in Heavy-NP Shift. *Journal of Memory and Language*, *39*(3), 392–417. https://doi.org/10.1006/jmla.1998.2586

Unsworth, N., Heitz, R. P., Schrock, J. C., & Engle, R. W. (2005). An automated version of the operation span task. *Behavior Research Methods*, *37*(3), 498–505. Retrieved from https://link.springer.com/content/pdf/10.3758/BF03192720.pdf

Valyear, K. F., Fitzpatrick, A. M., & Dundon, N. M. (2018). Now and then: Hand choice is influenced by recent action history. *Psychonomic Bulletin & Review*, 1–10. https://doi.org/10.3758/s13423-018-1510-1

Veale, J. F. (2014). Edinburgh Handedness Inventory - Short Form: A revised version based on confirmatory factor analysis. *Laterality: Asymmetries of Body, Brain and Cognition*, *19*(2), 164–177. https://doi.org/10.1080/1357650X.2013.783045

Washburn, M. F. (1916). *Movement and mental imagery: Outlines of a motor theory of the complexer mental processes.* Boston: Houghton Mifflin.

Wasow, T., & Arnold, J. (2003). Post-verbal constituent ordering in English *. *Determinants of Grammatical Variation in English*, 119–154. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.206.643&rep=rep1&type=pdf

Weigelt, M., Rosenbaum, D. A., Huelshorst, S., & Schack, T. (2009). Moving and memorizing: Motor planning modulates the recency effect in serial and free recall. *Acta Psychologica*, *132*, 68–79. https://doi.org/10.1016/j.actpsy.2009.06.005

Weiss, D. J., & Wark, J. (2009). Hysteresis effects in a motor task with cotton-top tamarins (Sanguinus oedipus). *Journal of Experimental Psychology. Animal Behavior Processes*, *35*(3), 427–433. https://doi.org/10.1037/a0013964

Wickelgren, W. A. (1969). Context-sensitive coding, associative memory, and serial order in (speech) behavior. *Psychological Review*, *76*(1), 1–15. Retrieved from http://www.columbia.edu/~nvg1/Wickelgren/papers/1969aWAW.pdf

Wolpert, D. M., & Landy, M. S. (2012). Motor Control is Decision-Making. *Current Opinions in Neurobiology*, *22*(6), 996–103. https://doi.org/10.1016/j.conb.2012.05.003