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Working memory and second language development: A complex, dynamic future?

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Abstract

Working memory (WM) is inherently dynamic and complex, being a multi-faceted system that links storage and processing components; yet it is widely understood as internal. Hence, in second language (L2) research, its connection to complex dynamic systems theory (CDST) remains underspecified. This paper seeks to bridge a gap between CDST and WM in L2 research. First, definitions of WM are reviewed, along with evidence for its relationship to L2 outcomes. Next, a brief overview of CDST highlights its metatheoretical and methodological implications. Three perspectives are presented to illustrate how WM can be viewed in terms of major tenets in CDST. These consider WM effects as: (1) context-dependent, (2) interrelated with those of other variables, and (3) amenable to change across the lifespan. Despite this reappraisal, numerous challenges remain. Thus, in addition to noting research opportunities, the paper also considers measurement issues, such as the determination of boundaries and selection of appropriate timescales. In closing, while WM studies have shown its influence on L2 proficiency and processing, to more fully understand its dynamic nature, what is needed is further research on the reciprocal influences of bilingual development and changes in WM components, such as control of attention.

Keywords: individual differences; working memory; complex dynamic systems theory; second language development; theoretical complementarity

1. Introduction

The goal of this article is to offer a state-of-the-art review of working memory (WM) and second language (L2) development that situates WM within complex dynamic systems theory (CDST). The view offered here has consequences that may inform research agendas incorporating cognitive IDs, as well as the conceptualization and procedural stages of measuring WM in L2 research. As to the question of whether WM is complex and dynamic, the answer, in some respects, is a simple *yes*. Ellis (2005) has invoked WM as the home of “explicit deduction, hypothesis formation, analogical reasoning, prioritization, control, and decision-making” (p. 337), implicating it in language learning and use. There is also abundant evidence that WM capacity increases throughout childhood and declines later in life (Alloway & Alloway, 2013; Gathercole & Alloway, 2008; Park & Payer, 2006; Simmering & Perone, 2013). In L2 research, these changes have been viewed as having the potential to explain issues such as the critical period hypothesis (Brooks & Kempe, 2019; Newport, 1990).

There is an expanding body of studies using WM measures in adult L2 learning and processing that informs a number of key areas in second language acquisition (SLA) research. However, this literature does not often seem to reflect the long-term trajectory of WM development. This seems surprising given that lifespan changes in WM are well-documented. SLA studies may target a narrow population, such as high school or university language learners. Or, they may regard WM as a control variable which is less relevant than the study’s primary foci. The tendency in SLA research to rely on cross-sectional designs (Doughty & Long, 2003) is at least partly to blame for this situation, though calls for longitudinal work have resonated throughout the field for some time now (Ortega & Byrnes, 2008).

Given the proliferation of studies orienting to L2 learning as a complex, dynamic system, and their potential to advance our understanding of IDs (e.g., Lowie & Verspoor, 2019; see also Dörnyei, 2017, MacIntyre, MacKay, Ross, & Abel, 2017), the time is ripe to reassess how WM is treated in L2 research. This conceptual review article will describe findings on WM and L2 learning, consider ways that such research may be compatible with CDST, specify reasons for considering WM as more than a static variable, and close by arguing that viewing WM as dynamic is more an opportunity than a challenge.

2. What is working memory and why does it matter?

2.1. Defining working memory

As described by Baddeley (2007, 2012), *working memory* is a psychological construct that evolved from views of memory as a simple, temporary storage space (or short-term memory) to a multi-componential model, comprised of a central executive and two storage systems: the phonological loop and the visuospatial sketchpad. These fluid systems, to which the episodic buffer was later added, interact with the so-called crystallized systems including visual semantics, episodic long-term memory (LTM), and language. Each of the aforementioned components serves distinct functions in the multi-component model. The phonological loop helps to retain speech for long-term learning through storage and rehearsal. The visuospatial sketchpad, likewise, facilitates rehearsal of visual and spatial information. The episodic buffer, which is the model's newest component, functions to integrate chunks by binding information from various sources into episodes. As Baddeley (2019) explained, it combines "visual and verbal information together with their semantic associates. A simple example might be a ringing alarm clock" (p. 289). These three storage components are regarded as limited in capacity, and they serve the central executive, the role of which is to focus and divide attention, switch tasks, and connect with LTM. In sum, WM involves storage, rehearsal, and processing.

Baddeley's (2012) multicomponent model of WM (see Figure 1a), originating in the 1970s, has informed countless studies in psycholinguistics and SLA, and its longevity is impressive considering that there are a number of competing proposals. For instance, other WM models include Cowan's (2005) embedded processes model (Figure 1b), which emphasizes the role of central executive processes during attentional focus within activated LTM, as well as Engle, Kane and Tuholski's (1999) resource-dependent inhibition model (Figure 1c), which posits that individual differences in the ability to control attention underlie WM capacity (for theoretical overviews, see Conway, Jarrold, Kane, Miyake, & Towse, 2008; Miyake & Shah, 1999). The notion of WM has even sustained the counter argument that emerging processing capacity could better account for IDs in language comprehension (MacDonald & Christiansen, 2002). What these three WM models all have in common is that each assumes a major role for executive processes, specifically those involving attention, and links them to LTM. This role is clear from the label and the prominence of the *central executive* in the three model visualizations depicted in Figure 1.

Therefore, it is useful to consider, from the outset, the view of attention adopted within WM models. In Baddeley's own words, "the capacity to direct and focus attention is perhaps the most crucial feature of working memory" (2007, p. 124). Returning to this model, it is assumed that behavior is controlled either automatically (e.g., in my case, reading from left to right in English) or via the mechanism of a supervisory attentional system (e.g., overriding this habit when reading Japanese *tategaki* text from right to left). Such supervised control is conscious, although it has been proposed that WM could operate outside of consciousness (Hassin, Bargh, Engell, & McCulloch, 2009). Nonetheless, Baddeley (2007, p. 306) clearly states that WM depends on conscious awareness, which is necessary for explicit L2 learning, whether such learning is intentional or incidental (see Schmidt, 2012).

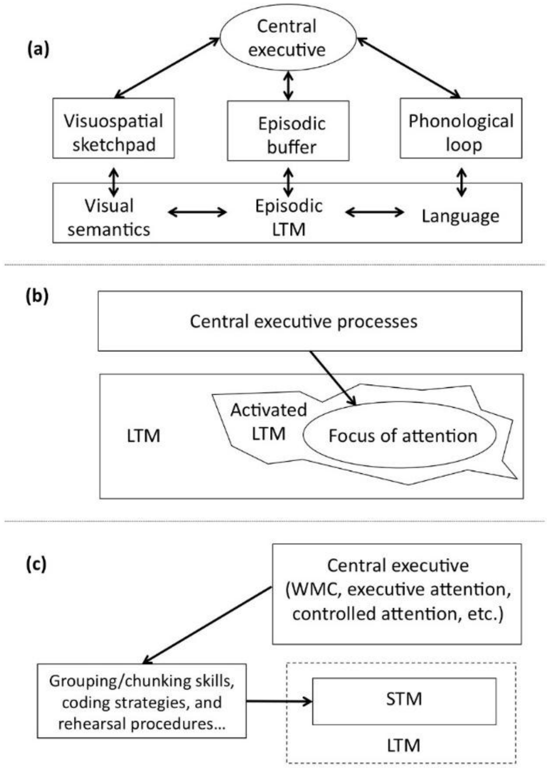

Figure 1 Three models of WM: (a) Baddeley's (2012) multicomponent model, (b) Cowan's (2005) embedded-processes model; and (c) Engle and colleagues' (1999) model (LTM = long-term memory; STM = short-term memory; WMC = working memory capacity)

2.2. The role(s) of WM in L2 research

Empirical studies applying WM models to investigate issues in L2 learning and performance have been published since the early 1990s. The expanding literature has been reviewed at various times (e.g., Juffs & Harrington, 2011; Robinson, 2003; Williams, 2012) and has resulted in a research synthesis of WM measures (Watanabe & Bergsleithner, 2006), a large-scale meta-analysis of the results (Linck, Osthus, Koeth, & Bunting, 2014), and a recent book-length survey (Wen, 2016). This section will attempt to briefly summarize major themes and findings that have emerged from this corpus of research, focusing on six strands of SLA research in which cognitive IDs are relevant, as identified in Granena, Jackson, and Yilmaz (2016).

These strands included: (1) aptitude theory, (2) instructed SLA, (3) comprehension and production, (4) novel SLA, (5) psycholinguistic approaches to bilingualism, and (6) transfer of training. Measurement issues, as another area of potential interface between WM and SLA will be considered later (see Section 4.2.). The emphasis here will be on recent studies, which may not have been previously reviewed. The most recent comprehensive review by Wen (2016) covered studies from 1992 to 2015. In the time since then, this literature has expanded considerably. For reference, a search of the ERIC database for peer-reviewed studies published between 2016 and February 2019, with specifications for the keyword *second language*, with *working memory* included in the abstract, yielded 53 publications, of which 45 reported on empirical studies. What follows is a selective review based on only a portion of these studies, as well as others published as book chapters. For each area of SLA research, a brief summary of what is known, and what recent research adds, will be provided.

Aptitude theory: WM has long been theorized to play a key role in foreign language aptitude, whether it is regarded as central to it (Miyake & Friedman, 1998) or as a primary cognitive ability that contributes to ability factors which comprise aptitude complexes for, for example, learning from recasts (Robinson, 2007). Categorizing L2 aptitudes according to whether they are (a) domain-general vs. domain-specific and (b) implicit vs. explicit, Skehan (2016) characterized WM as both domain-general and explicit. In the macro-SLA aptitude model (Skehan, 2016; Wen, Biedroń, & Skehan, 2017), WM is associated with a range of L2 cognitive processes, including input segmentation, noticing, pattern recognition, complexification (or, the adoption of more structurally complex constructions), feedback handling, and error avoidance. Evidence from a recent large-scale meta-analysis reveals that executive WM was moderately correlated with overall aptitude and one of its components, phonemic coding ability, while phonological STM (PSTM) showed weaker or non-significant correlations with these constructs (Li, 2016). This suggests that executive WM, in particular, plays a role in ones' ability to learn an L2.

Instructed SLA: Studies of SLA in instructional settings have for some years examined correlations between WM and processes in instructed L2 learning (e.g., Mackey, Philp, Egi, Fujii, & Tatsumi, 2002). These studies can be designed to provide insight into possible WM-treatment interactions (see Vatz, Tare, Jackson, & Doughty, 2013, for review). To a lesser degree, longitudinal work has also shown that WM predicts the development of proficiency in classroom-based instruction, after controlling for GPA, SAT, and motivation scores (Linck & Weiss, 2011).

Three recent studies that used the framework of task-based language teaching (TBLT) are briefly reported here. First, Wen (2018) found that executive WM (but not phonological WM) was significantly related to the use of formulaic sequences in L2 English during a narrative retelling task, regardless of whether planning time was provided. In another planning study, with learners of L2 Chinese, Li and Fu (2018) revealed consistent, significant correlations between an operation span test of WM and measures of accuracy and fluency under an unpressured, within-task planning condition, but not a strategic planning condition. Finally, Zalbidea (2017) manipulated task complexity, finding that operation span correlated with linguistic measures of performance in L2 Spanish on complex (but not simple) versions of an argumentative task, in both spoken and written modalities. Such studies suggest that instructional conditions in TBLT differentially engage WM, sometimes facilitating performance.

Comprehension and production: One of the findings of the meta-analysis by Linck et al. (2014), who reviewed data from 79 independent samples including over 3,700 participants, was that positive relations with WM held across outcomes targeting comprehension and production, as well as those incorporating both skills. In light of this result, the authors suggested that WM studies could focus on its role in specific L2 processes across skills (e.g., lexical access during reading versus speaking). In spite of this suggestion, most studies seem to focus separately on either comprehension or production. The TBLT studies just reviewed are an example of the latter, as they used L2 production as the outcome. As for a recent study of comprehension, Sagarra (2017) stands out for its longitudinal focus. The study examined whether WM predicts improvement in L2 Spanish grammar and reading comprehension. Despite initially finding no effect for WM, in a follow-up experiment, beginning L2 Spanish learners showed gains over one semester of instruction, which were related to a WM measure with a taxing processing component. This study points to the challenge of identifying WM tests with predictive validity over the long-term.

Novel SLA: There have been, for many years, studies that address the role of WM at the initial stages of SLA (see Kempe & Brooks, 2016, for a comprehensive review of this work). These theoretically motivated studies use language input unfamiliar to participants (i.e., artificial, semi-artificial, or miniature natural languages) to explore the conditions and IDs that shape early SLA. For instance, a study reported by Jackson (2016) hypothesized that variation sets, or partially repeated sequences found in child-directed speech, would support cognitive comparison (Doughty, 2001), and thus yield lower correlations between WM and learning of morphology in an artificial language. This claim was partly supported by the results, which further showed that mixed-effects models incorporating awareness and WM provided the best fit to the data. Other recent studies, particularly those targeting novel syntax, have not shown significant correlations between WM and outcomes (McDonough & Trofimovich, 2016). Thus, while WM is an important predictor in incidental L2 learning, its status in learning aspects that participants may be less aware of remains unclear (see Jackson, 2013).

Psycholinguistic approaches to bilingualism: The topic of WM in bilingual research raises particularly puzzling challenges. As Biedroń and Birdsong (2019) put it, "the chicken-egg problem of whether multilingual experience enhances WM capacity, or whether it is WM capacity that augments FL success, is unresolved" (p. 313). The cognitive consequences of bilingualism are often discussed in terms of executive function, which includes: (a) shifting, (b) updating (measured by WM operation span), and (c) inhibition (Miyake et al., 2000; see for discussion, Bialystok, 2018; Schwieter, 2016). Perhaps some of the most interesting recent evidence in this area comes from a meta-analysis conducted by Grundy and Timmer (2017). These authors pooled data from 27 independent studies (with over 2,900 participants) that examined WM performance amongst monolingual versus bilingual groups. They found a significant, positive mean effect size (ρ = .20), which showed that bilinguals had greater WM. Regarding the issue of causation, these authors noted that:

> . . . it is not likely that bilinguals in the present study became bilingual because of greater WM capacity, nor is it likely that monolinguals in the present study became so because of smaller WM capacity . . . we propose that second language experience has a positive effect on WM capacity. (Grundy & Timmer, 2017, p. 334)

So, it seems that while WM facilitates L2 processing and learning under certain conditions, it is also the likely the case that an individual's experience of living with two or more languages strengthens WM.

Transfer of training: Another element to consider when seeking to understand the bidirectional relationship between WM and L2 outcomes is that of training. Indeed, the case has been made that interventions designed to enhance WM could plausibly foster gains in L2 performance (Tsai, Au, & Jaeggi, 2016). A related, but different, view is that certain types of musical training, along with WM, foster abilities useful in acquiring specific aspects of an L2, such as phonology (Christiner & Reiterer, 2016). Due to a lack of studies, much more research is needed to examine these intriguing possibilities.

3. WM and L2 development through the prism of complex dynamic systems theory

The view of CDST adopted in this paper is based on Larsen-Freeman's (2015, 2017) presentation of it as a metatheory (see also de Bot & Larsen-Freeman, 2011). In her view, a metatheory presents concepts as broad in scope in order to seek out their interconnections, whereas a theory focuses on the particular details uncovered by empirical evidence (Larsen-Freeman, 2017, p. 21-22). Within CDST, a number of concepts relevant to second language development (SLD) have been identified. A system is understood to be a constellation of entities that function as a whole, and which are both embedded in larger systems and comprised of subsystems. Some concepts used to characterize systems include constant change, which is dependent on initial conditions, and related to this, context-dependency, as well as interconnectedness. Furthermore, systems are open, adaptive, and show nonlinearity. The remainder of this section will focus on ways in which WM is context-dependent, interrelated with other variables, and changes over the lifespan, in keeping with these core tenets of a complex, dynamic approach.

3.1. The context dependence of WM

As noted above, there is evidence to suggest that the extent to which WM is engaged during L2 processing and learning depends on the context or type of instruction. *Instruction* here can refer either to the pedagogic techniques used or the task instructions given to participants. Vatz et al. (2013) reviewed L2 instruction studies that reported interactions such that WM showed stronger relationships to outcomes in classroom conversations than in online chat rooms, as well as in recast versus metalinguistic feedback conditions. It may even be possible to trace such differences to the neurological level by using fMRI, as in a study reported by Li (2015). Here, participants were asked to do an artificial grammar learning task, under rule-search or exposure-only conditions. The data showed that the neural structures used by participants in these different groups overlapped, but their connectivity differed. Also, while both groups learned, WM correlated with performance only in the rule-search condition. This again points to the role of WM in explicit learning contexts.

3.2. Interrelationships between WM and other variables

The massive amount of research that has attempted to situate WM alongside other cognitive ID variables, such as intelligence, is impossible to summarize easily. Suffice it to say that WM can be regarded as a subsystem within the system of executive functions, defined as shifting, updating, and inhibition. Miyake et al. (2000) identified the operation span task as an indicator of updating, which they describe as “updating and monitoring of working memory contents” (p. 86). This ability is distinguished from, but related to, shifting between tasks and inhibiting prepotent responses.

Apart from these interrelationships between WM and other cognitive components, the relation to L2 factors must be closely considered. Previously, the link between WM and L2 aptitude was noted (see *Aptitude theory* in Section 2.2.). A study by Serafini and Sanz (2016; see also Serafini, 2017) shows how the effect of WM may be mitigated by L2 proficiency. Three proficiency groups (beginner, intermediate, and advanced) were tested at four times during and upon completion of instruction. Positive relationships between WM and L2 outcomes were clearest for the beginning learners, suggesting that WM is especially valuable at the initial stages of exposure and practice. It is worth noting, though, that participant attrition (the sample decreased from 87 to 33) could have influenced these results. This evidence for a decreasing role of WM contrasts with the meta-analysis by Linck et al. (2014), which reported similar, positive effect sizes for learners and bilinguals.

3.3. Changes in WM across the lifespan

Despite the fact that in research with adult L2 learners, WM is often conceptualized as more or less static, capacity varies among children, teenagers, and adults. Improvement is dramatic during childhood, with scores increasing steadily from age 5 to 15, when adult-like performance is attained (Gathercole & Alloway, 2008). Later, there is clear evidence for a gradual decline in WM ability from age 20 onward, in contrast to verbal abilities, which increase steadily with age (Park & Payer, 2006). However, cohort averages may not be helpful to understanding individual change. In addition to the robustness of this evidence, it is also clear that there are wide-ranging differences between individuals in each age group, and that different WM tests yield different results at any given age.

These basic facts are useful for understanding the scope and interpretation of effects in L2 studies on WM. Moreover, they also point to the need for careful sampling procedures and detailed reporting. For instance, in studies of younger L2 learners, age is often linked to grade level, as in Hansen et al. (2016), whose study focused on school children aged 7 to 14 years old. However, in university samples, the association between age and educational level may be less predictable, thus requiring researchers to establish careful sampling criteria. Studying college learners, Sagarra (2017) noted that only those between the ages of 18 and 30 were admitted, because “WM and processing speed start decreasing at the age of 40” (p. 348). In one of the few studies to focus on the role of WM among older language learners, Mackey and Sachs (2012) recruited participants between 65 and 89, explicitly justifying this age range. Note that in each of these studies a specific age range was provided. This is more informative than merely reporting average age, based on which readers cannot determine the potential influence of age-related variation in WM.

To conclude this section, as a means of better accounting for WM capacity increases from 2 to 15 years of age (as well as task-related variation), Simmering and Perone (2013) proposed that a dynamic account is needed. In their own words, WM “capacity does not exist in the way it has been traditionally conceptualized, but is an *emergent process within a dynamically coupled, self-organizing cognitive, and behavioral system*” (p. 16, emphasis in original). Advancing a dynamic view, according to their argument, requires: (1) specifying the coupling between cognitive and behavioral components in context, (2) linking theories to real-time behavior, and (3) seeking to integrate verbal and visual WM tasks, so as to gain insight into shared processes across domains. These recommendations might support future studies to better understand why WM varies across the lifespan, as well as to potentially inform research into differences in child versus adult L2 learning, where the effect of developing cognitive capacity is controversial (see Brooks & Kempe, 2019).

4. A CDST view of WM: Opportunities and challenges

In this section, I would like to return to the previously described issue of bidirectionality, frame this as a research problem that CDST seems equipped to explore, recast the bidirectionality issue in terms of the way relationships between variables are described in dynamic approaches, and then, finally, point out some challenges in implementing such research.

4.1. Opportunities

It turns out that the WM-SLD bidirectionality issue has been used as an example of how research based on a narrow theory may not, in fact, yield a complete understanding of processes in SLD, which is where a metatheoretical view shows its usefulness. As de Bot and Larsen-Freeman (2011) wrote:

> In the evaluation of theories, the notion of what constitutes proof is essential: A theory makes certain assumptions, and empirical data are gathered to test whether these assumptions hold or not. An assumption could be that there is a relation between the storage capacity in working memory and SLD . . . Another possibility is that people who practice learning an L2 a lot will have a larger working memory, so the larger memory capacity is a result and not a cause of language learning. (pp. 7-8)

To make matters even more complicated, this is not a dilemma that is easily resolved by looking to chronologically earlier stages of development. Interestingly, there are studies showing that visual WM develops in infants between 6 and 10 months (Simmering & Perone, 2013) and also that the bilingual advantage emerges as early as 7 to 12 months (Bialystok, 2018). However, by taking a more bird's eye view of this situation, especially one that incorporates the notion of change across time, CDST may promote greater clarity regarding the issues.

To begin with the evidence, a large-scale meta-analysis has demonstrated that WM predicts L2 outcomes overall (ρ = .25), in processing and proficiency, and that its role is evident in comprehension and production (and on measures combining these modalities), for both learners and bilinguals (Linck et al., 2014).

In contrast, WM was considered an outcome variable by Adesope, Lavin, Thompson and Ungerleider (2010) in a similarly large meta-analysis, which revealed positive effects for bilingualism on a range of cognitive measures, including attentional control and WM. So, there are opposite accounts, both of which are convincing, based on the evidence. Yet what remains to be understood is the direction of these relationships. Pointing out that their study was based on correlations, Linck and colleagues (2014) cautiously noted that the possibilities that (a) WM enhances L2 learning and use, and (b) L2 learning and use improves cognitive mechanisms, such as WM, are not mutually exclusive. Using a group design, the issue was again addressed by Grundy and Timmer (2017, see above), who provided evidence that bilinguals outperform monolinguals on WM span tasks, with an overall effect size of ρ = .20. To summarize, there is clear support for relationships between WM and SLD among those learning or using an L2, there is a positive association between bilingualism and several cognitive IDs, and there is a small WM advantage in bilinguals over monolinguals, which lends support to the view that bilingualism boosts WM, if only slightly.

At this point, it is tempting to accept Grundy and Timmer's logic, and to conclude that bilinguals owe this gain to L2 experience. This, however, is not the end of the story. First, as these authors noted, bilingualism is not a categorical variable, though it was treated as such in the studies they meta-analyzed. Second, it remains unclear precisely what kinds of experience comprise the necessary and sufficient conditions of this bilingual advantage. Therefore, these studies can guide future work that includes degrees of bilingualism and also, similar investigations focused on different language pairings, literacy levels, and social contexts. More importantly, though, whether they were based on evidence from correlational or group designs, each of these meta-analytic studies represents a cross-sectional approach. CDST, instead, focuses on dynamics over time.

Thus, the bidirectionality issue could be seen somewhat differently, in line with the view that "when one component changes, another component will change too, and the other way around" (Verspoor & van Dijk, 2011, p. 85). From this perspective, it is not a chicken-or-egg dilemma, but instead a matter of understanding the interconnectedness of these systems without assuming that simple causation can explain their growth. This new framing may be more appropriate for describing the interdependence of WM and language.

This paper has so far presented WM as dynamic and multi-componential, but what of language? That too, must be reassessed and explicitly defined to allow for a fuller understanding of the implications of CDST. Here is one relevant definition, which can be adapted to learning and use:

> Language, like the rest of perception and cognition, is a continuous trajectory through a high-dimensional state space that combines phonetic, semantic, and syntactic constraints for understanding with perceptual and motor constraints for continuously converting this developing understanding into successful bodily interaction with the environment. (Spivey, 2007, p. 206)

The experience of bilingualism involves juggling languages in a way that makes this trajectory perhaps all the more fluid. If we assume that system components are in constant motion, as do L2 researchers adhering to CDST, and as do Simmering and Perone (2013) for WM, then we should redirect our efforts to understanding their temporal dynamics.

While the evidence reviewed so far is intriguing, there is, it seems, very little that we know about the longitudinal growth within specific individuals of WM and bilingualism, both of which change and can be measured over time. Note that, to date, longitudinal studies of WM and L2 outcomes, which are relatively scarce, have typically measured WM at a fixed time point, using repeated measures only for the L2 variable. This is clearly not the only design choice possible. Verspoor and van Dijk (2011) offer a methodological overview of how study design can be informed by CDST, beginning with terminology which I will introduce here, before turning to an example of its application. First, various resources in the environment, in combination with IDs, foster the development of growers, or pairs of variables that exhibit a meaningful relationship. This relationship can be defined as supportive, competitive, or conditional. Supportive growers develop together, competitive growers inversely affect each other, and conditional growers entail a minimum level of one variable as a prerequisite for the development of another. For any given pair of components, or growers, the relationship can change across time.

Consider the case of a young adult learner, who, while simultaneously exposed to her L1, spends a considerable number of years learning a foreign language (L2), from junior high school to college, with brief periods of intensive study abroad, resulting in high proficiency. This period of learning is subsequently followed by a transition to a work environment in another country (where the L2 is dominant) and daily use of the L1 and L2, at which point the label *bilingual* becomes apt. In the initial stages of her learning, L2 development is supported by WM (as well as average or better motivation, aptitude, and strategy use). Upon transitioning to overseas employment, her WM benefits from her daily use of two languages. Of course, this is just one straightforward scenario of the many that could be offered. Assuming this case to be of practical interest, the possibilities in terms of the WM-SLD relationship, under a CDST account, may then be cast as research hypotheses.

For example, it seems reasonable to suggest that, as for viewing WM and SLD as connected growers, the relationship is initially supportive, with a moderate connection between these variables from the early stages of L2 development onwards (i.e., WM and SLD grow together). Recall that a positive relationship between WM and outcomes was found for both learners and bilinguals by Linck et al. (2014). Later, as WM begins to decline (after one's 20s), the daily use of two languages presumably has a facilitative effect on attentional control (discussed later, see Section 5.). Thus, the relationship here is conditional, as a certain level of daily use is needed to moderate the effect of aging on WM. Although speculative, the overall pattern seems likely to be asymmetric. The literature cited herein would suggest a certain degree of flux, as neither SLD nor WM remains entirely stable. To add to this, one could also assume that these relationships might vary according to proficiency-related factors, such as whether SLD is conceptualized as basic or higher language cognition (BLC vs. HLC, respectively), wherein BLC concerns grammar and lexis in speech reception and production, while HLC extends to low-frequency vocabulary and constructions, as well as written language, which are outside of typical daily usage (Hulstijn, 2015). Indeed, Hulstijn has suggested that WM is associated more strongly with HLC (p. 47). Given the varying degrees of biliteracy associated with SLD, it seems appropriate to consider these dimensions as well.

To measure the dynamic relationship between these growers would require a longitudinal design, in which both SLD and WM are measured repeatedly. As MacIntyre et al. put it, "evidence that best addresses the concerns of CDST is dense, longitudinal and individual" (2017, p. 99). Although such data are the backbone of CDST studies, as implied already, cross-sectional rather than longitudinal designs are presently the norm in SLA research on cognitive IDs, and the few longitudinal studies to date seemed to assume that WM was static for the duration of the study, as it was measured only once. Thus, there is a clear opportunity to expand research on WM and L2 learning and use in this direction, which possesses the distinct advantages of using CDST's metatheoretical and methodological insights to inform the vexing issue of how these variables may reciprocally influence each other. An initial attempt can be found in Serafini (2017), who argued that WM and other IDs enter supportive or conditional relationships. Furthermore, the visualization and modeling techniques described throughout Verspoor, de Bot, and Lowie (2011) offer sophisticated tools for analyzing longitudinal data.

4.2. Challenges

What, then, are the major challenges? Measurement of WM in this relatively new domain entails considering at least two distinct problems. These involve the scope and timing of measurement.

The boundary problem: As a conceptual problem, a focus on changes in WM and SLD unleashes a wide array of nested systems that could be studied. CDST is useful in that it makes explicit the need, as in any research endeavor, to draw a line somewhere with respect to the limits of an investigation. Larsen-Freeman (2017) described this "boundary problem" (p. 32) as one of delineating the system(s) of interest, yet acknowledging their connection to the wider ecology. Among cognitive IDs, and IDs in general, what insight is potentially lost by restricting the focus to WM? Amid personal development, and the growth of professional skills, what remains in the shadows when either BLC or HLC is in the spotlight? Choices have to be made. The foregoing sections indicate some plausibly relevant distinctions and foci, involving language (HLC), cognitive IDs (executive function), and time (childhood to early adulthood).

More diverse sampling can further extend the boundaries to expand our knowledge. For instance, there is a need for research on WM among younger learners (see Geva & Ryan, 1993; Hansen et al., 2016). Too few studies highlight the impact of geographic context, educational level, and socioeconomic status (but see Adesope et al., 2010). More insight can come from a focusing on a range of interlocutors (Gurzynski-Weiss, 2017). Finally, in a remarkable study, the effect of L1 structure on WM was recently demonstrated through an investigation with speakers of eight languages (Amici et al., 2019). Using a range of WM tasks, the recall performance of speakers of left-branching languages was better on initial than final stimuli, whereas the opposite trend was observed among speakers of right-branching languages, arguably because of differential processing demands across languages. In short, there are myriad connected systems to untangle.

The timescale problem: As a procedural – and practical – problem, the longitudinalness of investigations into WM and CDST is the next major challenge. Although detailed investigations of interrelatedness between system components can be done via cross-sectional sampling (Gass & Lee, 2012), many of its proponents view CDST as requiring longitudinal data (MacIntrye et al., 2017). With respect to the ID in question, WM changes on a timescale that is meaningful, but extends well beyond the reach of many empirical studies. Earlier, it was noted that more rapid growth is seen among children between the ages of 5 and 15 years old, and that decline is more gradual, potentially from age 20. Thus, WM is not comparable to a system such as willingness to communicate, which fluctuates over a matter of minutes (MacIntyre & Legatto, 2011, MacIntyre, this issue). In any case, the extent of change also depends on the individual. Though daunting, it may be useful to consider here conceptual macroscopic versus microscopic turning points (Ortega & Byrnes, 2008), the former referencing milestones in cognitive development, as well as key events in life histories, and the latter perhaps establishing gains through WM training. For example, Tsai et al. (2016) reported on a study in which third graders exposed to 12 days of training showed improvements in reading comprehension over a control group.

5. Conclusion

The construct of WM is inherently dynamic and complex, being a multi-faceted system that links storage and processing components, influences outcomes, and is shaped by time and experience. However, it is somewhat narrowly construed and measured in L2 research. Hence, its role remains underspecified at this time. This review has attempted to offer a reappraisal of WM and to identify the challenges and opportunities ahead. It has been argued that CDST invites closer consideration, especially, of the issue of reciprocal influences of bilingual development and changes in WM.

By way of limitations, this selective review has focused heavily on how CDST encourages a longitudinal approach to conceptualizing change and sampling data. However, the issue of time is best viewed in terms of the particular research questions at hand. The value of incorporating elements of CDST into studies that pertain closely to WM, but are not longitudinal, should also be acknowledged. Trait and state perspectives on IDs are complementary in the sense that they can address different dimensions of a given research problem, with the former appropriate for understanding structural relations and the latter suited to understanding temporal dynamics; however, they are not typically compatible in terms of their results, due to the ergodicity problem (see Lowie & Verspoor, 2019). Furthermore, the bidirectionality issue is not the only, or the most important, issue. Other key themes that may benefit from such focus as offered here, and throughout this special issue, include interactions between WM and other IDs, the role of WM under different learning conditions and with different L2 constructions, and the use of WM interventions to foster L2 learning and performance. As a practical example, Gregersen and MacIntyre (2014, pp. 87-97) offered several lesson plans integrating WM enhancement with instruction on verb tenses and formulaic expressions.

There is accumulating research evidence that WM supports SLD and that, conversely, bilingualism benefits WM. The mechanisms underlying this latter effect remain obscure, however. Bialystok (2018) has recently argued that executive function (i.e., switching languages, updating WM, and inhibiting active representations irrelevant to the target language) could be replaced by the construct of executive attention, which is closely related to the central executive component in Baddeley's (2007, 2012) model. It remains to be seen whether or not CDST can shed light on how "bilingual experience shapes attention throughout life" (Bialystok, 2018, p. 297). However, given the opportunities noted here, it seems likely that WM will have a complex, dynamic future.

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