Working Memory and Interpreting Studies

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Abstract: This chapter provides a systematic review of studies on working memory (WM) and interpreting published between the 1970s and 2010s, with special attention paid to simultaneous interpreting (SI) and consecutive interpreting (CI), which are the two primary modes of interpreting. Previous research, whether theoretical or empirical in nature, has investigated three major issues: (1) the interpreter's advantage over non-interpreters in WM capacity and executive control; (2) the relationship between overall WM capacity, WM executive control and interpreting performance, and (3) the interaction that takes place between long-term memory and WM to facilitate meaning retrieval from the source language, interlingual reformulation, and message delivery into the target language. Despite repeated attempts to illustrate how WM functions in the processes of SI and CI, however, there is a shortage of comparative studies that elucidate the similarities and differences in the role of WM in the two interpreting modes, in either theoretical or empirical research. This chapter will fill this gap in the research by first reviewing major WM models of interpreting to determine what SI and CI have in common and how they differ in processing routes; secondly by examining relevant empirical evidence that (in)validates such models, and thirdly by proposing new possibilities for research on WM in both SI and CI. By means of a synthesized review and an in-depth comparative analysis, this chapter will shed new light on how WM demand differs across interpreting tasks and fluctuates during the interpreting process, which will in turn contribute to future interpreting research and pedagogy.

Keywords: Working memory, simultaneous interpreting, consecutive interpreting, systematic review, comparative analysis

1. Introduction

Interpreting can be conducted either simultaneously or consecutively. In the simultaneous mode, interpreters listen, comprehend and translate the source speech in real time, which requires a coordinated use of limited working memory (WM) resources. In the consecutive mode, interpreters store the source speech in their WM, and then recall the stored speech in the target language by refreshing their WM (Dong et al., 2018). Both interpreting modes place high demands on the storage and processing functions of WM (Baddeley & Hitch, 1974) and require an effective executive control in WM operation (Nour, Struys, Woumans et al., 2020). Overall, previous interpreting research on WM can be divided into two strands. The first strand tests interpreters' and non-interpreter bilinguals' information storage and/or processing ability by measuring their WM capacity. The measurement is made using WM span tasks where subjects are required to recall a specific number of presented stimuli. The second strand investigates interpreters' operation of WM executive control, which includes three executive functions: inhibiting phonological and multi-tasking interferences (*Inhibition*), replacing old information with new information as a method of continuous input processing (*Updating*) and switching between languages and sub-tasks of interpreting from source speech comprehension to target speech delivery (*Shifting*) (Nour, Struys, Woumans et al., 2020). So far, contradictory findings have been reported regarding the benefits of interpreting training and working experience on WM capacity improvement and executive control enhancement.

Most of the studies in both strands deal with simultaneous interpreting (SI). This is because SI is generally considered much more demanding on the WM than consecutive interpreting (CI) and other interpreting modes (Dong & Cai, 2015) because of its concurrent execution of several sub-tasks from source speech processing to target speech delivery. Owing to the limited amount of research on CI, there is a lack of comparative discussions on the role of WM in SI and CI, the two most representative interpreting modes. This chapter attempts to fill this gap in the research by systematically reviewing previous research on WM in SI and CI, focusing on the common features and the differences between the two modes from theoretical and empirical perspectives.

2. Working memory in theoretical interpreting studies

2.1 The similarities between SI and CI

2.1.1 Demand on WM for language control and processing control

Baddeley and Hitch's (1974) Working Memory Model and Cowan's (1988, 1995) Embedded-process Model of Memory have been extensively discussed in interpreting studies. Baddeley and Hitch (1974) looked into the “inside” of WM by proposing two slave systems in WM: the phonological loop and the visuospatial sketchpad, which are responsible for audio and visual information processing respectively. Since the capacity of WM is limited, the two slave systems are coordinated by the commander in WM: the central executive. Through executive control, interpreters can effectively distribute WM resources to the audio channel (such as listening and speaking) and the visual channel (such as reading and note-taking). In contrast, Cowan (1988, 1995) focuses on the “outside” of WM by associating it with memory at different levels. In his model, WM is simply a “set of activated memory elements” (Cowan, 1995, p.100) that belong to long-term memory (LTM). Only when a memory is brought to the focus of attention can it be processed by WM. For example, when interpreters are processing the information in their focus of attention, they activate the part of LTM they need: linguistic knowledge and interpreting skills, for example, to accomplish comprehension or interpretation. The activated contents change constantly as the focus of attention moves. Overall, the two models explain how information is processed in interpreting with the two slave systems inside WM and with LTM outside it.

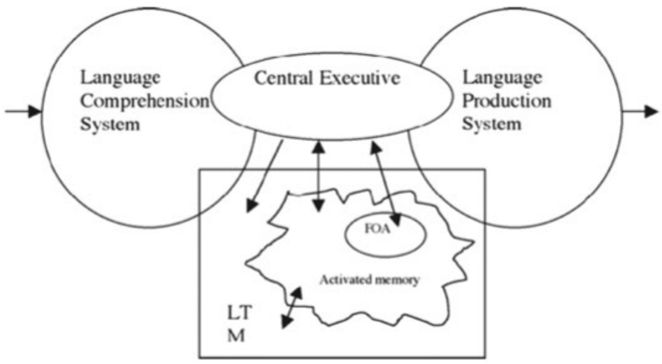

Figure 1.1 Mizuno’s (2005) model of interpreting based on Cowan’s (1988, 1995) Embedded-processes Model of Memory

Interpreting is a verbal task in nature and this should be reflected in WM models. With this in mind, Mizuno (2005) added a language comprehension system and a language production system before and after the memory section to Cowan’s (1988, 1995) Embedded-processes Model (see Figure 1.1). This addition seems to provide a complete description of the working flow of WM in interpreting from language input to language output. However, it neglects one of the most distinctive features of interpreting compared to other language processing tasks: language transfer (Dong & Cai, 2015). In SI, interpreters listen to one language and translate it into another language at almost the same time; in CI, by contrast, interpreters switch to the target language whenever the speaker finishes an utterance, and shift their interpreting direction when the source language changes. This frequent and regular switch between two languages is a distinctive feature of interpreting (Dong & Li, 2020) that should not be excluded from interpreting models. Therefore, Dong and Li (2020) proposed an attentional control model of SI and CI, taking both language control and processing control into consideration (p.10) (Figure 1.2). Under language control, working memory, together with monitoring, target enhancement, target disengagement and shifting, helps interpreters to focus their attention on inhibiting the source language and activating the target language. When a particular language input-and-output modality is established and transformed into a schema, interpreters can activate it whenever they need it. This is especially important for CI interpreters, who sometimes interpret for interlocutors from both sides. Whenever the source language changes, they must switch the inhibited language and the activated language accordingly. In this situation, WM is heavily relied on to achieve focused attention. Under processing control, WM and coordination enable interpreters effectively to divide their attention among the various tasks involved in interpreting, such as listening comprehension, note-taking, target speech production and self-monitoring. This is vital in SI where the degree of simultaneity of listening comprehension and target speech production decides the quality of the interpreting product.

It is worth mentioning that compared with previous models of WM in interpreting, Dong and Li's (2020) model not only illustrates how WM operates during the process of interpreting, but also shows how to build interpreting expertise. In this model, the establishment of a language-modality connection and the improvement of language processing efficiency respectively contribute to better language control and processing control. Specifically, during interpreting training, interpreters should learn to form language-modality schemas, enhance their language abilities and acquire interpreting strategies that will give them better attentional control. Hence, this attentional control model can be used not only as a process model of SI and CI, but also as a developmental model for interpreting training.

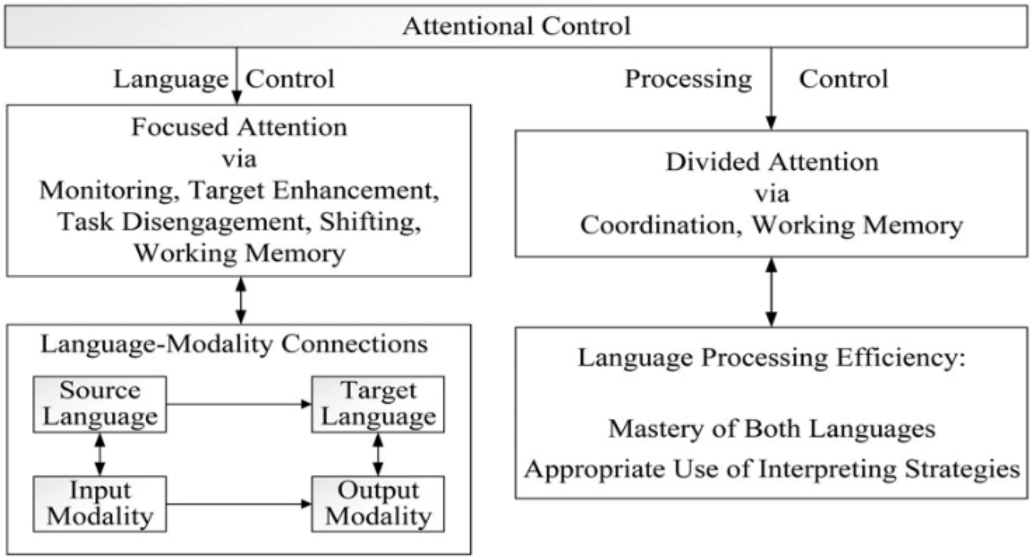

Figure 1.2 Dong and Li's (2019) attentional control model of interpreting

2.1.2 The role of WM in the development of interpreting expertise

Compared with other language processing tasks, interpreting is especially complex because of its cognitive demand on both information retention and the need for fast processing. This demand is decided by the speaker-paced feature of SI and CI. In SI, interpreters reformulate the information they have heard and articulate it in the target language while storing the continuous new input for later processing (Christoffels et al., 2006). In CI, interpreters must remember the whole source speech accurately and search for translation if there is any spare WM during listening. If an interpreter fails to keep up with the speaker, he/she will miss information, which will affect his or her comprehension of the source speech. To avoid information loss, interpreters can either increase their WM span to store more information, or release their WM space by automatizing some information-processing procedures.

Just and Carpenter (1992) observed that college students with larger reading spans had better language comprehension ability than those with smaller spans. Therefore, they claimed that the number of language elements (such as phrases and grammatical structure) individuals can activate in their WM decides the depth of language comprehension they can achieve. For interpreters, listening comprehension consumes at least 80% of their cognitive effort during interpreting (Padilla, 1995). If we put the two findings together, we can propose an assumption that a bigger WM span contributes to better language comprehension which could save interpreters' some effort in comprehension and improve their output quality during interpreting.

An alternative theory to explain Just and Carpenter's (1992) finding is the theory of expertise (Ericsson & Charness, 1994), which argues that experts outperform novices because of their extensive knowledge in a given domain. For example, if interpreters can process information in meaning chunks rather than individual words, even though the actual size of their WM remains unchanged, the amount of information contained in each unit increases. As a result, interpreters can store and process more information in their WM at a time. From a developmental perspective, once an individual is sufficiently proficient at performing a particular task, he or she can automize this operation, store it as a schema in LTM and use it at any time with little cognitive effort. For instance, Liu et al. (2004) reported that professional interpreters are more capable of detecting important ideas in speeches than novice interpreters, even though the two groups have a similar WM capacity. This is because professionals have automized this information-detection procedure in their LTM. Therefore, they can implement this procedure in WM without bearing much cognitive load. This interaction between LTM and WM has repeatedly been proved to be essential in providing specific skills and knowledge in tasks with high demands on WM, such as in playing chess (Holding & Reynolds, 1982) and computer programming (Adelson, 1984). However, in theories and models in interpreting studies, LTM is not always emphasized, in great contrast to WM.

So far, interpreting models which include LTM can be categorized into three kinds. Darò and Fabbro (1994) support an independent and sequential view of WM and LTM. They believe that language is first processed in WM and then in LTM. In WM, interpreters hold what they hear in their phonological loop and conduct sub-vocal rehearsal to keep the information highly activated. After that, they search in their LTM at all levels (episodic memory, semantic memory and procedural memory) for comprehension and interpretation. Interpreting is completed as soon as the search is done (see Figure 1.3). Ericsson and Kintsch (1995) proposed an interconnected relationship between WM and LTM, proposing the concept of long-term working memory (LT-WM). Specifically, when an interpreter has well-developed interpreting skills or when interpreting materials are familiar to the interpreter, he or she can activate corresponding interpreting knowledge in LT-WM with little cognitive effort. By contrast, Cowan (1988, 1995) and Mizuno (2005) proposed a hierarchical view of memory where WM is embedded in LTM (see Figure 1.1). When processing information, interpreters activate a sub-set of relevant items stored in their LTM and then transport them to WM. In this end, only a small fraction of the items will come into the focus of attention for further processing.

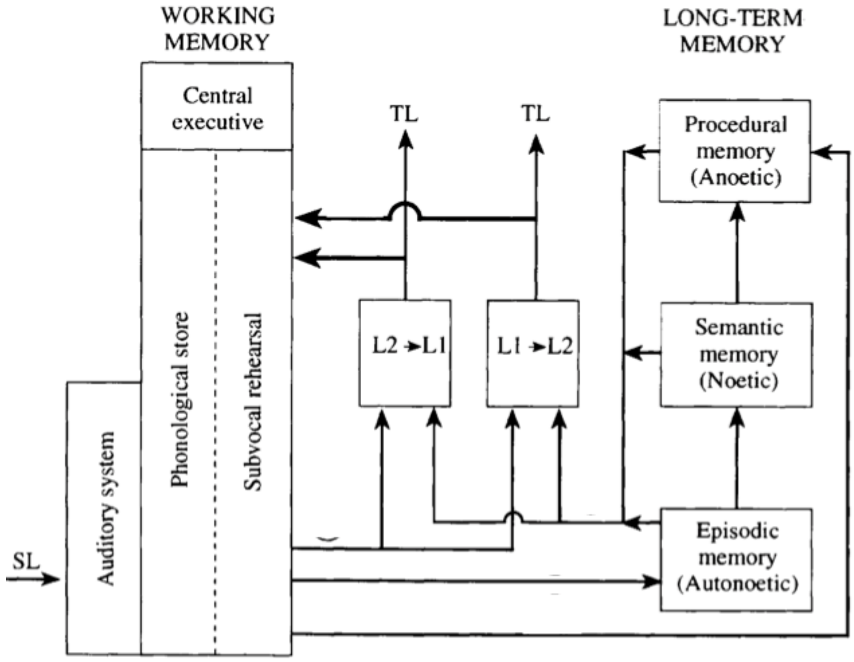

Figure 1.3 Darò and Fabbro’s (1994) model of simultaneous interpreting

The above three models illustrate the interaction between WM and LTM during the process of interpreting but not during the development of interpreting expertise. It is widely accepted that LTM is formed after learning from repeated practice with short-term memory. However, the process of this formation is not yet clear. According to Cognitive Load Theory (Paas & van Merriënboer, 1994), the WM-to-LTM transformation occurs when acquired knowledge and skills are transformed into schemas. When this condition is fulfilled, LTM can be enlarged, thus making available more capacity for other WM operations. However, this transformation requires interpreters to bear a particular type of cognitive load called germane load (Sweller, 1988), which is concerned with knowledge acquisition and procedure automation. To accomplish learning something, interpreters must be sure that their WM is not fully occupied by intrinsic load (decided by the task) and extraneous load (decided by the interpreter’s efficiency in WM use), which means that there is spare germane load in their WM.

2.2 The differences between SI and CI

2.2.1 Particular requirements of interpreting efforts

Gile’s (1997/2002) effort model has described how SI and CI differ in the types of effort required (for a detailed review, see Dong & Cai, 2015). Firstly, SI is a single-stage activity where listening (L), memorizing (M) and target speech production (P) happen simultaneously through coordination (C). By contrast, CI is a two-stage activity consisting of comprehension and reformulation. At the comprehension stage, interpreters listen to the source speech (L), memorize as much of the content as possible (M), produce notes for later memory retrieval (NP) and coordinate (C) these activities; at the reformulation stage, interpreters read their notes (NR), reconstruct the source speech from memory (SR), produce the target speech (P) and coordinate all of these activities (C). Therefore, CI is generally considered less demanding on WM than SI as there is more leeway with regard to task coordination and production time.

There are only four studies that have directly tested this assumption by comparing cognitive load in SI and CI from a product-oriented perspective, and three of these rejected this assumption. Lambert (1988) found that interpreters had similar free recall performance after SI and CI. It is assumed that the more demanding the task is, the smaller the number of recalled items will be. Therefore, his result suggests a similar level of cognitive demand across SI and CI. Gile (2001) and Russel (2002) respectively found higher accuracy in SI and CI renditions. Gile (2001) concluded that there was a WM overload in SI, while Russel (2002) came to the opposite conclusion – that there was a WM overload in CI. Liang et al. (2017) proposed a dependency distance approach to studying SI and CI products. Basically, the greater the distance between two syntactically related words, the higher the memory burden of an interpreter. They found that the distance is smaller in CI renditions than in SI renditions, indicating more cognitive load in the former than in the latter. So far, there has been no process-oriented research which has directly compared the cognitive load of SI and CI.

Secondly, although in both SI and CI efforts are required in the aspects of listening, memory, production and coordination, the two modes differ in the amount and type of effort required for each aspect. In SI, interpreters finish listening analysis, memory retrieval and output production within seconds, requiring fast processing in WM; in CI, interpreters comprehend and retrieve the source speech across the two stages of CI, respectively emphasising on the processing and storage functions of WM. Although no research has directly confirmed this assumption, Liang et al. (2019) indirectly support it through corpus analysis. In SI, they found interpreters relying on "the most tangible point of reference" (p.10) in the source speech to process language quickly owing to extreme time pressure, resulting in a more form-based interpreting. In CI, on the other hand, interpreters produced a higher frequency of functional words (as opposed to content words) than simultaneous interpreters to remind themselves of the syntactic structure of the source speech, producing a more meaning-based interpretation. In interpreting studies, form-based interpreting is considered faster and less effortful for it only requires shallow language processing, i.e., transcoding, while meaning-based interpreting is considered slower and more effortful for it involves deep semantic processing, i.e., deverbalization (e.g., Darò & Fabbro, 1994). Combing the results in Liang et al. (2019), both SI and CI rely on the processing function of WM, but the former involves language processing at a superficial level and the latter at a deep level. Moreover, the finding about more functional words in CI than in SI demonstrates interpreters' need in source speech memory retrieval, which greatly relies on the storage function of WM.

2.2.2 Demands on WM executive functions

SI requires concurrent listening comprehension and translation articulation, two activities that compete for the same cognitive resources in the phonological loop of WM. According to Baddeley and Hitch (1974), the phonological loop is comprised of two components: a temporary phonological store in which to keep perceived sounds and a sub-vocal rehearsal system for keeping the sounds active. It has been found that overt articulation hinders sub-vocal rehearsal, and information in the phonological store that is not rehearsed decays (Daró & Fabbro, 1994; Christoffels et al., 2006). This articulatory suppression effect explains SI's particular demand on WM to inhibit phonological interference. Specifically, while interpreters are articulating the translation of an earlier piece of information, they must inhibit the hampering effect this articulation poses on listening to newly coming in information. Darò and Fabbro's (1994) model reflects this phonological interference in SI (see Figure 1.3) by linking the auditory processing of the source text with the overt delivery of the target text (the arrow from TL (target language) points towards WM, as shown in Figure 1.3). This assumption has been confirmed by a series of studies, in which interpreters' recall performance after SI has been compared with that after other tasks such as listening, shadowing and listening with articulatory suppression (e.g., Lambert, 1988; Isham, 2000; Padilla et al., 2005). It was repeatedly found that recall after SI is worse than after other tasks, indicating a detrimental effect on memory caused by the phonological interference in SI. As a matter of fact, these findings provide empirical evidence for introducing phonological interference into future SI models.

In comparison, CI puts enormous pressure on the memory for complete and accurate recall of source speeches. So far, there is no model dedicated to WM operation in CI. Dong et al. (2018) interpreted Mizuno's (2005) process model of WM and interpreting from a CI perspective. They argue that *Updating* plays an essential role in CI. In the comprehension phase of CI, interpreters constantly update information in their WM as the source speech is delivered continuously; then, in the reformulation phase, they reactivate "the stretch of input which has already passed FOA (focus of attention)" to recall the source speech (Dong et al., 2018, p.3). In their empirical study, Dong and her colleagues also confirmed that *Updating* is a predictor of CI performance (for a detailed discussion, see section 3.2).

Another major difference between SI and CI lies in note-taking. When interpreting long sections, consecutive interpreters usually take notes to alleviate the pressure on their memory. From this perspective, CI is comprised of note-taking and note-reading. To complete note-taking, interpreters "translate" the verbal input from the phonological loop into written notes with the help of a visuospatial sketchpad, while in note-reading, they decode the visual notes and re-express them in the target language. In either process, the phonological loop and the visuospatial sketchpad work closely together and compete for the limited WM capacity. Therefore, interpreters must develop coordinating skills to balance these two components of WM. In WM executive control, note-taking is also a complex cognitive activity (Piolat et al., 2005). Firstly, interpreters shift between source speech comprehension and note production. During note production, they make a further shift between language-based notes and symbols. Secondly, interpreters constantly update information in WM to follow the source speech. Thirdly, they consistently inhibit the activation of inappropriate note forms, and sub-vocal rehearsal during writing. In summary, note-taking in CI places a heavy demand on the audio and visual components of WM and the three executive functions of WM. Note-taking research in its own right has found that students with larger WM spans experience less cognitive load in note-taking and cover more information in their notes in the classroom (Piolat, 2007). However, whether consecutive interpreters' WM capacity affects the quality of their note-taking and the amount of effort required remains under-explored.

3. Working memory in empirical interpreting studies

3.1 The similarities between SI and CI

3.1.1 Impact of interpreting training on WM span

Since the 1990s, interpreting researchers have been attempting to determine whether interpreters have an advantage over non-interpreters in WM span (Darò & Fabbro, 1994, Padilla et al., 1995). Tasks used to test WM span can be divided into two kinds, based on the two functions of WM: information storage and information processing (Baddeley & Hitch, 1974). The first kind only tests WM storage through simple recall tasks such as the digit span task. The other kind evaluates the integral use of the two functions using complex span tasks, such as recall after semantic judgement (Timarová et al., 2014). In both situations, researchers have hypothesized an interpreter advantage for two reasons: first, memory has long been considered to be a basic skill required for completing interpreting tasks (Gile, 1997/2002; Seleskovitch, 1968/1978); second, interpreters are consistently confronted with concurrent storage and processing demands during interpreting, from which they can develop WM skills that will enable them to tackle the issue (Timarová et al., 2014).

Overall, in previous research, in simple and complex span tests where digits, words and sentences are presented visually, interpreters have consistently been found to have an advantage over non-interpreters in terms of WM span, and professional interpreters have consistently been found to have an advantage over novices. However, it was also found that this advantage sometimes disappeared when the stimuli were auditory. This runs counter our expectation that interpreters would have an advantage in the auditory modality as they are consistently exposed to auditory processing. There are two possible explanations for this modality effect. First, “reading” words or sentences aloud in some reading span experiments actually gives subjects an opportunity to strengthen their visual memory using self-generated phonological codes (Penney, 1989). According to Penney’s (1989) model of short-term memory, auditory items are automatically encoded in acoustic and phonological codes, while visual items must be intentionally translated into verbal forms to generate phonological codes. If no rehearsal is involved, phonological codes can fade away in seconds. If visual-to-auditory translation is successful, people can trace their memory of the visual stimuli through codes in both visual and audio modalities. Hence, visual presentation with overt vocalization can be more traceable than auditory presentation alone, and therefore helps subjects to complete recall tasks. Secondly, more often than not, interpreters consult prepared speeches, slides, notes and other visual information during interpreting, thus developing a superior ability in visual-to-auditory translation. In comparison, non-interpreters practise this visual-to-auditory translation much less frequently. Therefore, they need more time to complete this translation procedure and create corresponding phonological codes. However, the longer they take, the more the memory decays. As a result, in the studies referred to here, non-interpreters did not outperform interpreters in visually-presented WM span tasks.

This modality effect was examined by several researchers and all of them rejected the idea that such an effect exists. Daneman and Carpenter (1980) found a high correlation between college students’ reading span and listening span. Köpke and Signorelli (2011) and Chmiel (2018) also reported similar reading and listening spans in interpreters. Thus, in previous studies, this modality effect might just have been a coincidence caused by non-standard experimental settings. Wen and Dong (2019) synthesized the findings of ten primary studies on interpreters’ WM and short-term memory. They found that whether interpreters had an advantage over non-interpreters in WM span depended on task type. An interpreter advantage was observed in verbal and numerical/letter span tasks but not in spatial tasks.

It is worth mentioning that in almost all studies on interpreters’ WM, researchers selected professional and novice interpreters according to the total time they had spent on interpreting work and/or training. However, few researchers have described the proportions of SI and CI in the interpreters' work/training experience. In Hiltunen et al. (2014), simultaneous and consecutive interpreters were compared to linguistic non-experts and foreign language teachers in a free recall task. They found that only the simultaneous interpreter group outperformed the linguistic non-expert group. This suggests that SI and CI affect the growth of WM size in different ways. Therefore, when recruiting interpreter subjects and describing their background, the proportions of SI and CI work/training experience should be considered as an important variable to be controlled for.

On the other hand, an increase in WM span has also been found to be related to higher interpreting accuracy and fluency. Tzou et al. (2012) reported that student interpreters had significantly larger reading spans than untrained bilinguals. And their interpreting accuracy of selected sentences and the overall speech was positively correlated with their reading spans. Lin et al. (2018) found a significant correlation between students' reading span and the number of interruptions and hesitations in their interpretation, concluding that WM is a powerful predicator of SI fluency. This is in line with Injoque-Ricle et al. (2015) and Macnamara and Conway (2016), who also reported a positive correlation between WM span and SI quality. With regard to CI, Dong et al. (2018) tested students' L2 listening span before and after CI training and found that the pre-test span predicted CI performance. Yenkimaleki and van Heuven (2017) compared the CI performance of a control group (with no memory skill training) and an experimental group (with memory skill training). A positive effect of memory training on reducing omissions in interpreting was observed, which indicates the benefits of an increased WM span on CI fluency. However, all of the above-mentioned studies were conducted with interpreter trainees. Timarová et al. (2015) conducted a study with professional interpreters and reported only a marginally significant correlation between interpreters' letter span and interpreting accuracy in figures. So far, little evidence is available of a relationship between WM capacity and interpreting quality among professional interpreters.

3.1.2 Novice advantage in simple and complex WM span tasks

Novice interpreters have repeatedly been found to produce similar or even better performance than professional interpreters in simple WM span tasks, and sometimes in complex WM span tasks. Based on a meta-analysis of ten studies on this topic, Wen and Dong (2019) concluded that expert interpreters outperform beginner interpreters but not intermediate interpreters in WM span tasks. It seems that the increase in WM span stops at an unclear point during the development of interpreting expertise. Several longitudinal studies conducted with novice interpreters have demonstrated the effect of interpreting training on WM span (Babcock & Vallesi, 2017; Dong & Liu; 2016; Nour, Struys & Stenger, 2020). However, there are contradictory findings concerning the effect of interpreting experience on WM span, with around half of the studies acknowledging professional interpreters' advantage (Nour, Struys & Stenger, 2020; Padilla et al., 1995; Tzou et al., 2011), and the other half denying such an advantage (Köpke & Nespoulous, 2006; Liu et al., 2004; Padilla, 1995).

There are two potential reasons why a novice might have an advantage in simple WM tasks. First, professional interpreters are usually older than novice interpreters, leading to an aging effect on WM span. Signorelli et al. (2011) proved that younger interpreters performed better than professionals in non-word repetition and cued recall, suggesting a trade-off between age and WM span. Second, compared with novice interpreters, professional interpreters usually process information in larger units. In this way, they can alleviate the pressure on their memory and focus more on language processing (Wen & Dong, 2019).

A novice advantage has also been observed in complex span tasks. Liu et al. (2004) used a CI-like WM task where subjects first processed semantic meaning and then recalled the last words of sentences. The results show that professionals and novices performed similarly. Köpke and Nespoulous (2006) tested subjects with a SI-like task of free recall with articulatory suppression and found that novices recalled more words than professionals. These findings challenged the conventional view that expertise in interpreting relies on a greater WM capacity. Köpke and Nespoulous (2006) speculated that professional interpreters have developed an optimal language processing route that releases them from the constraints of WM size. Novice interpreters without such optimal processing routes can easily experience an overload of WM during interpreting. It is not yet clear how this optimization of language processing works. However, to some extent it implies that the development of interpreting expertise is centred on domain-specific abilities like language processing rather than on general cognitive abilities.

3.1.3 Impact of interpreting experience on WM executive control

An interpreter advantage has not only been observed in WM span tasks which test interpreters' information storage and/or processing ability but also in tasks targeting on their operation of WM executive control. Overall, interpreters have been found to have an advantage in using the executive functions of WM, although the reasons for this advantage have not yet been clarified.

With regard to *Inhibition*, Dong and Zhong (2017) reported an effect of interpreting experience, finding that more experienced student interpreters outperformed both less experienced students and more balanced non-interpreter bilinguals in a Flanker task.

By contrast, Woumans et al. (2015) found that interpreters outperformed an unbalanced group of bilinguals but not balanced bilinguals in a Simon task and an Attention Network test[1], which implies that the (un)balance of bilingualism plays a decisive role in *Inhibition* execution. According to Nour, Struys, Woumans et al.'s (2020) detailed review of eight studies on interpreters' *Response-Distractor Inhibition*, interpreters only show an advantage when they are compared with unbalanced bilinguals and not when compared with balanced bilinguals.

With regard to *Updating*, Dong and Liu (2016) tested students' execution of this function through a *n*-back task[2] before and after CI training, and observed a significant improvement in students' task performance. They explain that in CI, interpreters repeatedly replace old information with new information during the input stage and that they refresh their memory of the source speech during the output stage. In this way, interpreters strengthen their *Updating* ability. This could explain why Morales et al. (2015) and Timarová et al. (2014) did not find an advantage on the part of simultaneous interpreters in this regard. In SI, interpreters usually release their memory immediately after finishing the interpretation of the current information. Nevertheless, simultaneous interpreters can acquire this *Updating* ability quickly. Morales et al. (2015) compared simultaneous interpreters' performance across the two blocks of a *n*-back task and found improved accuracy in the second block. In contrast, non-interpreter bilinguals showed no improvement throughout the task. Taken together, it seems that CI and SI experience have benefited the development of *Updating* in different ways.

In comparison, findings concerning the positive impact of interpreting training and/or working experience on *Shifting* have been consistent (Dong & Liu, 2016; Macnamara & Conway, 2014; Yudes et al., 2011), the only exception being Timarová et al. (2014). This is owing to the high sensitivity of *Shifting* to environmental factors. It has been found that over 20% of its variability is attributable to non-genetic factors (Nour, Struys, Woumans et al., 2020). In other words, the constant shift between languages during interpreting enables interpreters to improve their *Shifting* ability. In comparison, non-interpreter bilinguals face fewer *Shifting* needs in language use, resulting in slower reactions to shifting-related tasks. Moreover, interpreting is conducted under extremely high time pressure, meaning that interpreters must make *Shifting* decisions quickly. Compared with translators, who also switch between languages but with much lower time pressure, interpreters have been found to perform better in *Shifting*-related tasks (Henrard & van Daele, 2017).

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[1] These tasks are complex versions of a Flanker task.
[2] Subjects decide whether the current stimulus matches the stimulus presented *n* items earlier.

All in all, an interpreter advantage has been found in the execution of all three executive functions of WM, although how bilingual competence and interpreting practice interactively contribute to this advantage remains under-explored.

3.2 The differences between SI and CI

3.2.1 Working memory: *Inhibition* in SI and *Updating* in CI

The three executive functions of WM affect the sub-processes of interpreting differently (Timarová et al., 2014). In SI, there is an overlap between listening to the source speech and articulating the target speech for about 70% of the time (Chernov, 1994). Interpreters must therefore minimize the phonological interference caused by concurrent listening and speaking through *Inhibition* (e.g., Chincotta & Underwood, 1998; Padilla et al., 1995; Yudes et al., 2012). Moreover, the concurrent execution of sub-tasks like listening comprehension, interpretation delivery and self-monitoring requires interpreters to inhibit the interferences caused by multi-tasking. In CI, interpreters memorize the inputted source speech and retrieve it when producing the output. Their pressure mainly derives from having to refresh their memory of the source speech, ranging from single words to entire speeches (Dam, 2010, p.75), through *Updating* (Dong et al., 2018; Dong & Liu, 2016). In short, in SI the emphasis is on *Inhibition*, while in CI the emphasis is on *Updating*, but both require *Shifting* for language transfer.

To test simultaneous interpreters' *Inhibition* advantage in resisting phonological interference, researchers usually employ a free recall task with articulatory suppression. This task requires interpreters to articulate irrelevant sounds while listening to words or sentences, and thus creates an SI-like scenario. Using this task, Köpke and Nespoulous (2006) identified an interpreter advantage over non-interpreter bilinguals and a novice advantage over professional interpreters. Similarly, Padilla's team (1995, 2005) found that novice interpreters outperformed non-interpreter bilinguals whether they had high reading spans or not. However, it has been argued that the novice advantage in *Inhibition* might be misleading since the selected task does not resemble SI as assumed. The suppressed recall task did prevent sub-vocal rehearsal as SI does. However, it requires interpreters to listen to and voice irrelevant information, whereas SI requires interpreters to articulate a translation of whatever they have heard. Moreover, the words or sentences used in the task are usually unrelated to each other, while the input in SI is normally a logical and coherent text, which provides interpreters with contextual hints that facilitate better source speech comprehension and prediction. Therefore, when the adopted WM task does not resemble SI, more-experienced interpreters might not be able to show an advantage over less-experienced interpreters in *Inhibition*. An alternative explanation for no *Inhibition* advantage in more-experienced interpreters may be that *Inhibition* is essential in the early stage of interpreting training but not as essential in building interpreting expertise.

Research on *Inhibition* and multi-tasking has yielded more contradictory results than research on *Inhibition* and phonological interference in SI. A few researchers have reported an interpreter advantage in this regard (Köpke & Nespoulous, 2006; Woumans et al., 2015), while most researchers have denied it (Babcock & Vallesi, 2017; Dong & Xie, 2014; Dong & Liu, 2016; Yudes et al., 2011). Many of the tasks adopted in these studies focus on non-verbal information processing (arrows, shapes and colours). However, not all SI skills can be transferred to non-verbal or general cognitive tasks. Morales et al. (2015) found that interpreters did not present any advantage in conflict resolution, but they showed an advantage in alertness and orienting tasks, which involve multi-tasking as SI does. Similarly, Dong and Liu (2016) did not detect an interpreting training effect on interpreters' ability to resist conflicts, since interpreters are not often required to resolve conflicts of this kind during interpreting. All the above indicate that an interpreter advantage in *Inhibition* depends on the transferability of interpreting expertise to the adopted tasks.

In contrast, research on *Updating* and CI has yielded more consistent results. Dong's team first reported a positive impact of CI training on interpreters' *Updating* ability (Dong & Liu, 2016). Later, they found that students' *Updating* ability successfully predicted their CI performance both before and after CI training (Dong et al., 2018). Finally, they did a meta-analysis of four studies on *Updating* and interpreting and found that an interpreter advantage in updating ability had been observed in both CI and SI (Wen & Dong, 2019).

It is noteworthy that an improvement in updating ability was observed in subjects who had received CI training for the shortest time (a 32-hour in-class training programme) (Dong & Liu, 2016). However, no such improvement was witnessed in memory span (Dong et al., 2018), shifting or inhibitory control (Dong & Liu, 2016). Based on these findings, Wen and Dong (2019) concluded that "updating ability is probably the first taxed and trained memory skill in interpreting training relative to memory spans (short-term memory and WM spans)" (p.12). This might be caused by the speaker-paced feature of SI and CI. Without *Updating*, interpreters would not be able to make enough memory space available for new information. In comparison, *Inhibition* and *Shifting* are more necessary after new information has entered the WM and is competing with old information for WM resources. To verify this assumption, researchers should conduct longitudinal studies with non-interpreters who start to learn interpreting and novice interpreters who gradually gain more interpreting experience. In this way, researchers can find out how the three executive functions of WM develop along with the course of interpreting training and practice.

3.2.2 Local cognitive load in SI and CI

Cognitive load is "the load that performing a particular task imposes on the learner's cognitive system" (Paas et al., 1995, p.64). When it exceeds an individual's WM capacity, task performance drops or even crashes. For interpreters, there are "global" and "local" levels of cognitive load. At a "global" level, interpreting as a single task entails more cognitive load than shadowing and listening do (Christoffels & de Groot, 2004; Köpke & Nespoulous, 2006; Padilla et al, 2005). At a "local" level, cognitive load fluctuates throughout the whole process of interpreting. In SI, interpreters' cognitive load fluctuates below sentence level because they follow speakers closely to produce target speeches. But in CI, interpreters' cognitive load varies beyond sentence level because they can flexibly allocate cognitive resources to the two stages of CI, as long as the sum of the allocated resources does not exceed their WM limit. Most of the research on this subject has attempted to identify the factors that affect the local cognitive load of interpreting, while only few studies have directly measured the amount of cognitive load.

SI researchers have mainly measured interpreters' local cognitive load by analysing their interpreting products. It is assumed that interpreting quality drops as cognitive load increases. On interpreting accuracy, Gile (2017) asked ten professional interpreters to interpret the same materials twice. He found new errors and omissions at different places in the interpreters' second rendering, which indicates a change in the cognitive load fluctuation pattern between the two interpretations. On interpreting fluency, Plevoets and Defrancq (2016) took the occurrence rate of *uh(m)* as an indicator of local cognitive load and found that it was predicted by the delivery rate of the source text. In other words, local cognitive load increases as the speakers' delivery rate increases. Shao and Chai (2020) found that interpreters' local cognitive load reached a peak when processing four information chunks at one time. When they exceeded four chunks, interpreters' performance dropped dramatically. They also measured a specific kind of local cognitive load during interpreting: the concurrent load, which is caused by not finishing processing the current sentence. They measured it through ear-voice span (EVS), the time span between input and output, and it was found to be significantly correlated with SI performance. In other studies, the length of EVS has been found to increase with an increase in syllable and sentence length (Lee, 2002) and with an increase in syntactic and semantic complexity (Timarová et al., 2014), and to decrease with an increase in preparation time (Díaz-Galaz et al., 2015) and interpreting experience (Timarová et al., 2014, but not in Christoffels & de Groot, 2004). Although those researchers did not interpret EVS from the perspective of local cognitive load, they provided empirical evidence that the online cognitive load of SI changes within a sentence. Seeber (2011) measured interpreter's concurrent load using pupillometry, and found that interpreters' pupils dilate more towards the end of sentences while handling asymmetrical structures in SI. This might be attributed to the four interpreting strategies interpreters adopted in this SI task: waiting, stalling, chunking and anticipating. Among the four strategies, the first three allow interpreters to wait in order to obtain more information. Therefore, interpreters' local cognitive load accumulates towards the end of sentences.

In contrast to SI, very few studies have measured local cognitive load in CI. Wu and Wang (2009) analysed the case of an interpretation delivered at a press conference held by the Chinese government and found that interpreters can save cognitive efforts by simplifying sentence structures in source speeches. They identified three simplification methods: deleting the overlapping part of different sentences, transforming sentences into the same structures, and merging sentences with similar structures. Chen (2017) measured interpreters' ear-pen span during note-taking and eye fixations during note-reading. The data suggest that notes that entail longer ear-pen span and cost more cognitive efforts during note-taking result in shorter fixations and less cognitive effort during note-reading. In other words, there is a trade-off in cognitive load across the two phases of CI.

All in all, interpreters experience fluctuating local cognitive load during interpreting. The amount of load varies within sentences in SI and beyond sentences in CI. More process-oriented research is needed to unveil the complex fluctuation pattern of local cognitive load during the interpreting process.

4. Discussion

Based on a systematic review of interpreting research on WM capacity and executive control, we observed that in most cases interpreters showed an advantage over non-interpreters in these regards. However, more-experienced interpreters and less-experienced interpreters were alternately found advantageous than each other concerning WM capacity and executive control. From theoretical and methodological perspectives, these findings could lay the ground for future empirical research in this field.

First, the inconsistent findings about the benefits of interpreting experience accumulation on WM might be derived from the mismatch between participants' interpreting experience and the WM task selected. On the participant side, CI demands information storage during input and *Updating* for recall during output, while SI requires fast information processing and *Inhibition* for resisting phonological interference. The two interpreting modes contribute to the growth of WM in different ways. On the task side, researchers can test interpreter's information storage and processing ability with simple and complex memory span tasks in visual and audio modalities, or their executive control with tasks specifically targeted at the three WM executive functions. Thus, if consecutive interpreters were tested using information processing tasks or simultaneous interpreters were tested using information storage tasks, then more-experienced interpreters may not be able to show an advantage over less-experienced interpreters in the tested aspect of WM. Future research should strictly control the variables involved in experimental designs to ensure that interpreters' CI and SI experience composition or the selected WM task are not confounding factors affecting the research outcome.

Second, a great deal of research has been conducted on WM in SI, while little attention has been paid to CI in this regard. Among those SI studies that included WM capacity control in their participant selection, almost all use recall tasks containing an input stage of stimuli presentation and an output stage of stimuli recall, which resemble CI tasks more than SI tasks. In other words, researchers tested interpreters with the same ability in CI-like tasks and correlated this ability with interpreters' SI performance. Therefore, WM tasks involving separate input and output are suggested for CI research, and those requiring simultaneous input and output are advised for SI research. Moreover, it would be interesting to compare WM demands and interpreters' coping strategies across the two stages of CI. At present, students usually receive CI training before SI training, as CI ability is generally considered to be a prerequisite for completing SI tasks. To decide whether this order is reasonable in curricula design, more empirical evidence from comparative research on WM in CI and SI would be necessary.

Third, concerning the contradictory findings regarding WM and interpreting quality, more process-oriented research should be conducted to see how WM demand fluctuates during interpreting from beginning to end. The process-oriented methodology has been used in several pioneering SI and CI studies which recorded interpreters' eye movements, galvanic skin responses and other physiological responses during interpreting (e.g., Chen, 2017; Seeber, 2011). These studies have proved that interpreting is a dynamic process, during which interpreters experience cognitive adaptation and emotional fluctuation. However, there is a challenge in measuring the three types of cognitive load (intrinsic load, extraneous load and germane load) separately, and in differentiating positive emotions (such as excitement) from negative emotions (such as disappointment). If cognitive load can be measured separately, the amount of germane load can reveal how many WM resources are devoted to "learning" during interpreting. Researchers could measure student interpreters' germane load and score their interpreting performance before and after interpreting training. By dividing students into high-score and low-score groups, researchers could compare how different the two groups are in terms of the amount of germane load they devoted to learning and the quality of the interpretation, further illustrating the formation of interpreting expertise. Similarly, if positive and negative emotions can be presented separately, researchers will be able to understand better how interpreters deal with the overwhelming stress during interpreting. For instance, if more excitement correlates with better interpretation, then motivation enhancement would be an essential aspect for interpreting trainers to consider during curricula design.

Looking ahead, research on WM and interpreting would benefit from investigating several under-explored issues. First, interpreting in general is beneficial to the growth of WM. However, it is not yet clear how SI and CI contribute to this growth and in turn benefit from the growth through enhanced interpreting quality. Second, little attention has been paid to CI, in which the two stages of input and output place different demands on WM, leading to a shortage of comparative discussions on the role of WM in CI and SI. Third, cognitive load fluctuates during the process of interpreting, giving rise to the question of how speaker-related variables such as delivery speed and interpreter variables such as interpreting strategies affect the pattern of cognitive load fluctuation during interpreting.

5. Conclusion

This chapter has reviewed the operation of WM in SI and CI from theoretical and empirical perspectives. Theoretically, both interpreting modes place high demands on WM for language control and processing control. SI centres more on fast information processing because of its requirement for an immediate input-to-output transformation, while CI emphasises on both information processing and storage because of the need to recall source speeches. Empirically, WM and interpreting have been found to be interdependent on each other in a complex way. Questions remain regarding the development path of WM during the course of interpreting training and its interaction with interpreting performance. Future research could combine process-oriented and product-oriented approaches to unveil the cognitive mechanism governing the interpreting process and modulating the interpreting quality.

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