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Investigating Cognitive Mechanisms Underlying Working Memory Manipulation Across Linguistic and Non-Linguistic Domains of Bilinguals

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Abstract

Cognitive control is a mental construct thought to be important in most cognitive tasks, including second language learning. Its functions are believed by many scholars to be mainly domain-general, with some transferability across linguistic and non-linguistic domains. Our study aims to investigate to what extent the domain-generality claim of working memory (WM) between the visual and verbal domains is true in Thai adults aged 18-36 years old. Subjects maintain and manipulate contents in the computerized WM tasks in the verbal (English, Thai, and Mixed Thai-English) and visual (kaleidoscope) domains. We hypothesized that (1) there are correlations in the WM manipulation effect of behavioral performances within the verbal domain, and (2) there are correlations in the WM manipulation effect of behavioral performances between the verbal and visual domains. Behavioral results (hit rates and reaction times) indicate significant correlations among the WM manipulation effect among the three language tasks, but not between the language and the visual tasks. Implications include that cognitive training and improvement are possible, but only within the domain. The manipulation effect can be trained across different languages using linguistic tasks, but visual tasks may not produce the desired manipulation effect in the verbal tasks. Cognitive trainings that use both linguistics and non-linguistic tasks simultaneously to train the students' WM are recommended to achieve the manipulation effect in the language domain.

INTRODUCTION

Over the past decades, Thailand has spent several billion baht each year to improve English language literacy and proficiency in Thai students with little success (Hayes, 2016; Jarunthawatchai & Baker, 2024; Kaur et al., 2016; Snodin, Savski, & Sameephet, 2024; Thitiratsakul, 2024; Trakulphadetkrai, 2011). To solve this problem, English programs have recently been implemented in more than 2,000 public schools and the Ministry of Education plans to recruit over 10,000 native English-speaking teachers to improve English proficiency in Thai students (Bangkok Post, 2021; Ministry of Education, 2019). However, since Thailand has a large education gap, more than 40,000 schools, especially in provincial areas, still use Thai as the main language of instruction as it is the country's only official language (Darasawang, 2007; Ministry of Education, 2019). Thus, Thai adults are not competitive globally because they have insufficient English language proficiency (Chenaksara, 2005; Luankanokrat, 2011; Mala, 2018; Snodin et al., 2024; Wiriyachitra, 2002).

To be able to reduce this gap, the country needs more than 10 times of the current budget to expand the English programs to these schools and create additional English training programs in workplaces nationwide. This is nearly impossible given the economic slowdown Thailand has faced (Ministry of Education, 2019; Suthiwartnarueput, 2021). Implementing these English programs is not an easy task because it requires a lot of money, human resources and effective teaching/learning methods suitable for students and adults who have little exposure and experience using English in their learning and work environments (Kaur et al., 2016; Punthumasen, 2007). In 2023, Thailand ranked 101st out of 113 countries in a global ranking of countries and regions by English skills conducted by Education First (EF) on adult population (median age = 25 years old) (Education First, 2023). This ranking is considered by EF as very low proficiency, lower than other Asian countries such as Cambodia (98th), Vietnam (58th), and Indonesia (79th).

The majority of these Thai adults have passed the critical period for second language (L2) acquisition, which is around two years of age until around 17 years old. This period is thought to be the age range that acquisition of L2 yields better results than at any other age. Thus, it is vital for linguists and scientists to develop successful English learning and/or transitioning programs for these adults, but we now lack the fundamental knowledge about the underlying cognitive processes crucial for second language learning (Hernandez et al., 2021; Vanhove, 2013).

In cognitive neuroscience, these cognitive processes are called cognitive control, which is a group of important human brain or mental processes that take the goals we wish to achieve into account and influence and/or alter our behaviors in hope of achieving those goals. Cognitive control is thought to be domain general and consists of several core functions (Lehto et al., 2003; Miller & Cohen, 2001; Miyake et al., 2000; Morton et al., 2011). One of these functions is working memory (WM) that allows for short storage and manipulation of the information coming from sensory inputs such as our eyes and ears. The researchers focus on WM processes because WM is fundamental to the acquisition of new vocabularies into long-term memory (Baddeley, 2012; Cattell, 1963; Ellis, 1996). A larger WM storage has been linked to a larger vocabulary size, better word recall and higher verbal fluency (Atkins & Baddeley, 1998; Bialystok & Feng, 2009; Carpenter et al., 2020; Luo et al., 2010). The capacity of WM and the ability to manipulate contents in WM (i.e., WM manipulation) could be enhanced via cognitive training by varying memory load demands, rehearsal, and/or manipulating the information stored in WM with new incoming sensory information (Dahlin et al., 2008; Jensen & Tesche, 2002).

Also, WM processes are thought to involve neural activity implicating in the prefrontal cortex and the basal ganglia, brain regions critical to a variety of cognitive control functions and thought to be domain general (Chein et al., 2011; Cools & D'Esposito, 2011; D'Esposito & Postle, 2015; Ekman et al., 2012). Therefore, we may be able to use one sensory input to enhance the WM performance of another e.g., training on the ability to perform in the visual domain may help increase the ability to perform in the sound and language domain. Thus, WM is a fundamental construct that subserves the information coming into both the explicit and implicit memories. If WM can be trained to improve, the benefits encompass both the second language acquisition (information coming into implicit memory) and learning processes (information coming into explicit memory).

The present study aims to (1) investigate the cognitive mechanisms underlying working memory manipulation across different languages in Thai-English bilingual adults and (2) to test the generality of the cognitive processes underlying working memory manipulation between the linguistic and non-linguistic domains in Thai-English bilingual adults. It is hypothesized that (1) there are correlations in the working memory manipulation effect of behavioral data (hit rate and reaction time) between languages (Thai, English, Mixed) and (2) there are correlations in the working memory manipulation effect of behavioral data (hit rate and reaction time) between the languages (Thai, English, Mixed) and visual domains.

The researchers pose two questions (1) Do Thai-English bilingual adults use the same cognitive mechanism that supports working memory manipulation across languages? (2) Do Thai-English bilingual adults use the same cognitive mechanism that supports working memory manipulation across linguistic and non-linguistic domains?

LITERATURE REVIEW

Cognitive control

Cognitive control or executive functions refers to the mental processes needed when a person has to focus on the task at hand and behave in such a way that the intended goal could be achieved. The three main core functions or components of cognitive control are inhibitory control, working memory (WM) and cognitive flexibility (Diamond, 2013; Lehto et al., 2003; Miller & Cohen, 2001; Miyake et al., 2000; Morton et al., 2011). These components form the basis for higher-level cognitive functions such as planning, reasoning, and problem-solving (Cattell, 1971, 1987; Diamond, 2013; Haier, 2017).

Cognitive control is essential in language learning because it guides our behaviors in the direction that would achieve the goal of learning (Gathercole, 2006; Gupta, 2003; Service, 1992; Swanson, 2003). Laufer (1990) points out that acquiring vocabulary in a second language is a crucial step in mastering that language. We use this particular subcomponent of cognitive control, WM, in the process of successful word learning in both our first and second languages (Avons et al., 1998; Cheung, 1996; Gathercole & Masoura, 2005; Majerus et al., 2006). The better quality the new words is stored in WM, the better the word representations become in our long-term memory. In other words, good verbal WM leads to good memorization of words (Baddeley et al., 1998; Gathercole, 2006).

Research suggests that the human brain is malleable and capable of being improved, so we may be able to use one sensory input to enhance the WM performance of another. Previous studies found that cognitive training protocols that target both the prefrontal cortex and the basal ganglia could potentially improve cognitive control processes across linguistic and non-linguistic domains (Anguera et al., 2013; Calkins et al., 2015; Krause & Kadosh, 2013; Schmiedek et al., 2010; Strobach et al., 2016). These protocols could be effective ways to help enhance second language (L2) learning in individuals who have passed the critical period.

Bilingualism

Bilingualism is the state of possessing more than one language system within a person (Dronkers & Baldo, 2009). Many studies have sorted bilinguals into different categories, namely compound-coordinate-subordinate bilinguals and simultaneous-sequential bilinguals. Compound bilinguals learn their two languages at the same time, so they have two sets of languages to describe one meaning concept. Coordinate bilinguals learn the two languages in different contexts, such as home vs school, so they develop two separated sets of words used to describe two meaning concepts in their mind. Subordinate bilinguals refer to those who learn a second language in adulthood. They have a strong language, the mother tongue, and they learn a second language through their mother language. They usually translate their second language back to their mother language, so they possess only one meaning concept. Then, simultaneous bilinguals are introduced to the two languages at roughly the same time, very early in life, while sequential bilinguals are introduced to the second language after the age of three when they already mastered their first language (Castilla et al., 2009; D'Acierno, 1990; Diller, 1970; Klein et al., 2014; Moradi, 2014).

However, there is no clear and standard boundary separating bilinguals and monolinguals since people define bilingualism differently. Recent efforts have defined bilingualism as a spectrum of experience – the period until two or more language systems are present in an individual (DeLuca et al., 2019; Luk & Bialystok, 2013). A number of factors contribute to this spectrum - language proficiency, frequency of language use, age and order of language acquisition, and sociolinguistic context (Friesen et al., 2015; Kaushanskaya & Prior, 2015). Among these factors, proficiency and frequency of use are more important in determining a baseline of sufficient proficiency in a second language for a person to become a bilingual (Bedore et al., 2016; Grosjean & Li, 2013).

Since bilinguals can vary within themselves in terms of when they acquire their second language (L2) in relation to their native or first language (L1), it is suggested that scientists should compare simultaneous bilinguals and monolinguals when studying bilingualism since simultaneous bilinguals are the ideal representation of the bilingual population group. However, this is not always practical in the real world where proficient bilingual research subjects are difficult to find.

The use of two languages of bilingual people requires the continuous storing and processing of the language system which brings about the demands and changes on the cognitive functions. This confers a hypothetical superiority of the bilingual brain to a monolingual one. Literature reports several areas where being bilingual is considered more cognitively advantageous than monolingual, such as better attention and cognitive control (Alladi et al., 2013; Altarriba, 2006; Badre & Wagner, 2007; Barker & Bialystok, 2019; Bialystok & Viswanathan, 2009; Bialystok et al., 2007; Hayakawa et al., 2017; Javor & Javor, 2016; Singh, 2018). This suggests that being bilingual can positively affect our cognitive abilities. Thus, it is a desirable goal to achieve.

Human memory systems

In our memory system, incoming information get briefly stored and/or manipulated in *working memory*. *Short-term memory* concerns only the brief storage of information while WM encompasses both the brief storage and processing of information such as updating or manipulating it within that brief period. After a few seconds, the information is either passed on to the long-term memory or get lost through forgetting. The *long-term memory* stores the information permanently as the general knowledge we know about the world, further classified as declarative or explicit memory and non-declarative or implicit/procedural memory. *Declarative memory* is the conscious memory about facts and information. It is where we consciously encode, store and retrieve information including word forms and meanings (Eichenbaum, 2004; Squire et al., 2004; Ullman, 2001; Ullman, 2004). Declarative memory can be divided into two subcategories. *Episodic memory* is the memory about the events and personal experiences that have occurred through time. We remember them in episodes or scenes. *Semantic memory* refers to the memory about concepts, ideas, knowledge, and meanings.

Non-declarative memory takes place unconsciously and can be divided into four subcategories. *Skills and habits* are the way we normally do things in our life, such as speaking a second language fluently after learning and practicing it intensively (Morgan-Short et al., 2014; Schacter, 1987). After repeating the information learned in declarative memory many times, it gradually moves to the non-declarative memory and becomes automatic (Kandel, 2007). *Priming memory* is when exposure to one stimulus, usually words or objects, unconsciously influences our brain to have a better or worse ability to recognize a subsequent stimulus (Mayr & Buchner, 2007; Tulving & Schacter, 1990; Weingarten et al., 2016).

Classical conditioning refers to the learning process that results from an unconscious association between a particular stimulus and response (Bouton & Moody, 2004). *Habituation* is defined as “a decrease in responsiveness due to the presentation of a repeated stimulus” (Jumonville, 2012, p. 24).

Bilingual memory systems

The two languages of bilinguals have been represented in the Revised Hierarchical Model (French & Jacquet, 2004; Kroll et al., 2010) which posits that bilinguals have the same underlying concept of a word, but the concept is more strongly represented in their native language (L1) than in the second language (L2) since the bilinguals are usually more familiar with the word's meaning in their L1. The lexical link from L2 to L1 is stronger than that linking L1 to L2 since the bilinguals normally encode the words in L2 together with its translation back to L1, thus reinforcing the encoding of the lexical link from L2 back to L1. However, it happens frequently that the words in L1 are not matched with its translations in L2.

The connectionist models give further explanations regarding mechanisms that enable bilinguals to use their two languages without failure such as interferences from the other language not currently in use. One major model is the Bilingual Interactive Activation Model Plus (BIA+) (Brysbaert & Duyck, 2010; Dijkstra & Van Heuven, 2002) proposing that visual input activates recognition of the features (e.g., basic lines and shapes) and these features activate the recognition of the letters corresponding to themselves. The sequence of these letters activates recognition of the words corresponding to the sequence and inhibits recognition of the words that are not related to the sequence. After that, the words activate recognition of the language corresponding to the words and inhibit recognition of the language that does not include those words. The activated language also exerts inhibition to the other language not currently in use.

All of these activations happen only when they reach the recognition threshold of each stage. The activation that is not strong enough to reach the threshold value does not activate the next stage of activation. Bilingual lexical access is non-selective (Altarriba & Heredia, 2018), meaning several words can be activated at the same time, but only the ones passing the threshold activate the next stage of recognition.

Working memory

Working memory (WM) is a fundamental cognitive system that provides an active space for sensory and mnemonic information to be temporarily stored and manipulated so that we could learn to form abstract thoughts and control complex behaviors, including language comprehension and production (Acheson & MacDonald, 2009; Daneman & Merikle, 1996). According to the Multi-component Working Memory Model, WM is a centralized system, where the prefrontal cortex supervises its processes of information. WM also consists of multiple fluid systems including visual-spatial sketchpad and phonological loop (Baddeley, 2012; Baddeley & Hitch, 1974). These systems interact with the crystallized systems responsible for amassing long-term knowledge such as visual semantics, language, and episodic long-term memory.

Phonological loop plays a major part in language processing, providing an active storage for us to acquire unfamiliar words and learn to associate these words with their meanings, visual images, contexts, or words that we have learned (Baddeley, 2000; Baddeley et al., 1998). To some extent, the greater the capacity and efficiency of the phonological loop are, the greater the vocabulary size, verbal fluency, and the speed of acquiring foreign vocabulary become (Blom et al., 2014; Gathercole, 2006; Gathercole & Baddeley, 1989; Papagno et al., 1991). When we want to register phonological sequences of new vocabulary into long-term memory, the brain needs to create representations for these sound sequences.

Unfortunately, information in the real world is often temporary and does not wait for the brain to create the representation of the information. To register this fleeting information, our brain needs a system that temporarily holds the information while it is being accurately registered into the long-term memory. We do not need a system that registers every new information it receives from the environment into the long-term memory nor a system that simply repeats the knowledge already stored in the long-term memory, but the one that is sensitive enough to incrementally register new information based on a repeated characteristics in the short-term storage system. The information that keeps repeating itself is useful enough to be encoded for use in the long run (Baddeley et al., 1998; Sasisekaran et al., 2010).

Brown and Hulme (2013) suggest that phonological loop contributes to the successful formation of new vocabulary in long-term memory through the interactions among vocab size, lexical representation, nonword repetition ability and other factors. Greater vocab size leads to more segmentalized lexical representations and improvement in repetition of nonwords or phonemes, which in turn, leads to greater vocab size. Young children first store words and sounds they hear from the environment together in one large group, without any need to segment or sequence them since there are not a lot of words at this stage.

As they grow older, they keep encountering more words from the external world and some words or parts of words sound similar. Thus, they need to start segmenting and organizing their vocabulary into similar groups according to the lexical representations of the words (Jusczyk, 1993; Metsala, 1997; Metsala & Walley, 2013). Then the number of words keep increasing, so they must continue to the smaller level of nonword or phoneme, which is the smallest unit of sound that distinguishes a word from the other words in a particular language (Baars & Gage, 2013). The improved ability to distinguish between phonemes leads to better temporary storage of new vocab in the phonological loop and the vocab acquisition to the long-term memory. The greater vocab size results in better distinguishing of phonemes and other factors such as spellings or the physical looks of the words could lead to more segmentalized lexical representations.

Research on bilingual working memory

While bilingual advantages in attention, inhibitory control, cognitive flexibility, and other domains of cognition have been consistently reported and generally accepted, evidence for bilingual advantages in WM processes remains controversial with mixed findings. Morales et al. (2013) as well as Blom et al. (2014) report that bilingual children have better WM than monolingual children in both the visuospatial and verbal domains, especially in WM tasks that include processing or updating of the memory contents i.e., tasks involving the central executive. Cockcroft et al. (2019) report that multilinguals perform better than monolinguals on all of the WM components i.e., visuospatial maintaining, visuospatial manipulating, verbal maintaining, and verbal manipulating.

On the other hand, Bonifacci et al. (2011) report no bilingual advantage in WM when they ask the bilingual children and young adults to remember numbers and symbols. Engel de Abreu (2011) reports no WM advantage of the bilinguals compared to the monolinguals. Ratiu and Azuma (2015) put bilingual and monolingual young adults through four WM tests and does not find bilingual advantage in WM, suggesting that bilingual advantages may take place only in tasks involving central executive. Namazi and Thordardottir (2010) study the interaction between controlled attention and WM between bilinguals and monolinguals. Although they report a relationship between WM and controlled attention, they do not find a bilingual advantage in terms of WM.

A meta-analysis study by Grundy and Timmer (2017) reviews 27 independent studies on bilingualism effect on WM and reports a small to medium effect size supporting the view that WM capacity is higher in bilinguals than in monolinguals. These mixed results might emerge from the fact that WM tasks employed in most studies could not effectively dissociate different cognitive processes described in the Multi-component Working Memory Model, particularly the maintenance and the manipulation processes, which are related to the fluid and the central executive systems, respectively.

Thus, here the researchers adapt the previously established WM task from another neuroscientific study investigating WM manipulation (Itthipuripat et al., 2013), so that it could be used in this study to effectively track the maintenance and manipulation processes across linguistic and non-linguistic domains, as well as examine the effect of bilingualism on behavioral performance.

By varying cognitive loads, or the amount of information that the human WM can process at a time (Van Merrienboer & Sweller, 2005), between the maintenance and manipulation conditions, the researchers expect to see the differences in the behavioral results. Normally, the manipulation condition, where the subjects have to remember a higher amount of information and cognitively manipulate the information in their WM, demands more cognitive load than the maintenance condition, where the subjects remember a lesser amount of information and do not have to manipulation information in their WM.

METHODOLOGY

Subjects and task conditions

Twenty-six native Thai speakers, aged 18-36 years old with normal or corrected-to-normal vision and no history of neurological or psychiatric disorders were recruited. The focus was given to this group because their prefrontal cortex and subcortical region called striatum have reached developmental maturation while still not shown signs of decline as in dementia (Alladi et al., 2013; Bialystok et al., 2007; Somerville & Casey, 2010). In this age range, these brain areas are still capable of being developed given appropriate task goals (Braver et al., 2009; Zanto & Gazzaley, 2013). The subjects are subordinate bilinguals. They learn a second language in adulthood and have a strong first language. They learn a second language through their first language and they usually translate their second language back to their first language, so they possess only one meaning concept. Also, they are sequential Thai-English bilinguals who were introduced to the second language after the age of three when they already mastered their first language.

The subjects were recruited from a community nearby King Mongkut's University of Technology Thonburi (KMUTT) through posters posting both on-site and online channels. The subjects were provided with a written informed consent, issued by the Institutional Review Board at KMUTT. The subjects filled in the questionnaire to reveal their ages and proficiency levels of the English and Thai languages.

Table 1 introduces the tasks and task conditions used in the verbal and visual domains as well as maps them to the hypotheses

Table 1
Tasks and task conditions in the verbal and visual domains

Hypothesis	Domain	Task	Condition
1) There are correlations in the working memory manipulation effect of behavioral data (hit rate and reaction time) between languages (Thai, English, Mixed).	Verbal	English	Maintenance
		Thai	Manipulation
			Manipulation
		Mixed English-Thai	Maintenance
			Manipulation
2) There are correlations in the working memory manipulation effect of behavioral data (hit rate and reaction time) between the languages (Thai, English, Mixed) and visual domains.	Visual	Visual	Maintenance
			Manipulation

The maintenance condition refers to the condition that subjects only remember the sound or picture items shown to them in sequence, and respond by selecting the pictures shown on the screen in that sequence. The manipulation condition refers to the condition when subjects remember the sound or picture items shown to them in a sequence. After the sequence ends, a new item is added and subjects must abandon the first item in the sequence from their memory and put the new item at the last position in the sequence to create a new sequence. Subjects respond by selecting the pictures shown on the screen according to the new sequence.

These two task conditions provide behavioral data called hit rate and reaction time. The hit rate is the percentage of accuracy, indicating what percentage of the tasks that subjects respond correctly. Reaction time (RT) is the time that subjects use to respond to the tasks, indicating how long subjects use to respond measured in the unit of milliseconds (msec).

Instruments

There are two instruments employed in this study. First, the adapted version of the Language and Social Background Questionnaire (LSBQ) (Anderson et al., 2018; Li et al., 2006) was adapted to be used with the subjects to inquire their current ages, onset ages of L1 and L2 learning, and proficiency levels of the English and Thai languages (min = 1, max = 10) (see Appendix A).

Then, two computerized cognitive tasks that were designed for the subjects to perform for half a day. These tasks measured their performances (hit rate and reaction time) in WM maintenance and manipulation (Itthipuripat et al., 2013). These tasks are the Verbal-working -memory task and the Visual-working-memory task that will allow us to investigate the correlation within the verbal domain and between the verbal and visual domains.

Experimental procedures

The experiment took half a day (maximum 3.5 hours, including experiment preparation and breaks). It was conducted one-by-one in a quiet environment. The subjects performed the experiment by sitting comfortably in front of a computer screen in an air-conditioned room, so they can pay good attention to doing the experiment. The experiment consists of two tasks, the verbal-working-memory task and the visual-working-memory task. No practice trials were given to the subjects. The subjects were only given PowerPoint presentation explaining the experiment details, sequence of the sounds and pictures, and actions they have to take during the experiment.

The Verbal-working-memory task

The first experiment was the verbal-working-memory task (Figure 1). This task was used to investigate the effect of bilingualism on cognitive mechanisms underlying WM manipulation in the language-specific domain. Specifically, the task investigated if the experience using one vs. two languages lead to cost or benefit in the adults' ability to update information contents in the first and the second languages as well as when they had to use both languages at the same time.

In this task, there were three language conditions, Thai, English and Mixed Thai-English. The subjects, sitting in front of a computer screen, listened to and remembered the list of word sounds in sequence in a language condition, and remembered them during the first delay period (Delay#1). The interstimulus interval (ISI) was 0 second. The delay is 1.5s long because the authors would like to look at manipulation effect within working memory, not sensory memory or long-term memory, which have shorter and longer durations, respectively. The sounds were presented through speakers.

After Delay#1, a new item appeared either as a noise or a new word. If the subjects heard a noise, a musical note at middle C, they must continue remembering (maintain) those words during the second delay period (Delay#2). During the response phase, they had to choose the pictures corresponding to the words they had previously remembered in sequence by pressing the keyboard buttons corresponding to the pictures on screen. However, if the subjects heard a new word instead, they had to make a new sequence of words by forgetting the first word in their memory and adding the new word to the end of the sequence (manipulate). During the response phase, they had to choose the pictures corresponding to the words they had previously remembered in sequence by pressing the keyboard buttons corresponding to the pictures on screen. This is called one trial of the task.

There are overall 40 trials in the task for one language condition, dividing equally into two halves. In 20 trials, the subjects maintained the information they remembered and answered in sequence. In the other 20 trials, they manipulated the information and answered in sequence. These two halves of the trials were randomly mixed with each other, so the subjects could not guess whether the next trial would ask them to maintain or manipulate the words they heard. Trials that include only four different word sounds during the encoding phase were equally mixed with trials that include four-word sounds with one word sound presented twice, so they actually consisted of three different word sounds. The researchers performed one 40-trial verbal-WM task for each language condition (Thai, English, and Mixed Thai-English), Thus there were the overall 120 trials for the three language conditions.

Note that in the Mixed Thai-English tasks, the presentation order of language is pseudo-randomized across trials in both the maintenance and manipulation conditions. Also, the Thai (L1) and English (L2) words used in this study are one-syllabic and frequently-used words e.g., หมา-dog, แมว-cat, ผึ้ง-bee. These words are carefully selected for this study to ensure that all of them are easy enough for all the subjects to understand.

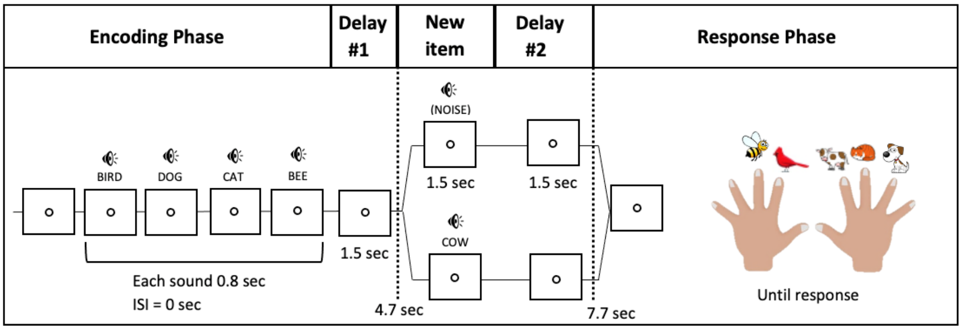

Figure 1 The verbal-working-memory task

The visual-working-memory task

To test the generality of the bilingual effect on cognitive processes underlying WM manipulation in the non-linguistic domain, subjects performed the variant of the visual-working-memory task (Figure 2). In this task, there was only one visual condition. The subjects, sitting in front of a computer screen, saw and remembered the abstract images in sequence and remembered them during the first delay period (Delay#1). The interstimulus interval (ISI) was 0.5 second. The one-and-a-half-second delay allows the authors to see manipulation effect within the process of interest, working memory. This reduces possible interferences from other memory systems such as sensory memory and long-term memory.

After Delay#1, a new item appeared either as a "#" sign or a new image. If the subjects saw a "#" sign. They must continue remembering (maintain) those images during the second delay period (Delay#2). During the response phase, they had to choose the pictures corresponding to the images they had previously remembered in sequence by pressing the keyboard buttons corresponding to the pictures on screen. However, if the subjects saw a new abstract image instead, they had to make a new sequence of images by forgetting the first image in their memory and adding the new image to the end of the sequence (manipulate). During the response phase, they had to choose the pictures corresponding to the images they had previously remembered in sequence by pressing the keyboard buttons corresponding to the pictures on screen. This is called one trial of the task.

There are the overall 40 trials in the task, dividing equally into two halves. In 20 trials, the subjects maintained the information they remembered and answered in sequence. In the other 20 trials, they manipulated the information and answered in sequence. These two halves of the trials were randomly mixed with each other, so the subjects could not guess whether the next trial would ask them to maintain or manipulate the images they saw. Trials that include only three different images during the encoding phase were equally mixed with trials that include three images with one image presented twice, so they actually consisted of two different images. The number of images in this task is different from the number of sounds in the Verbal-working-memory Task in order to control task difficulty. The tasks are designed to be difficult enough for the subjects to put in their effort to successfully complete them, but not too difficult to make the subjects abandon all their efforts. The researchers performed one 40-trial task for the visual task, so there were the overall 40 trials for a visual condition.

Note that in the Mixed Thai-English tasks, the presentation order of language is pseudo-randomized across trials in both the maintenance and manipulation conditions.

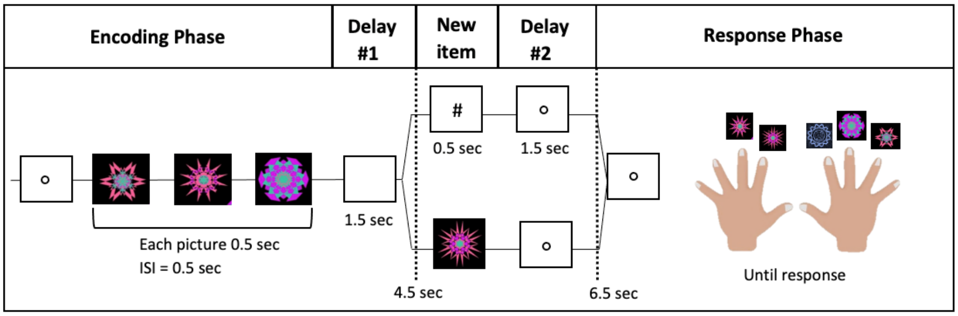

Figure 2 The visual-working-memory task

Both the verbal- and visual-WM tasks, consisting of 40 trials of Thai, 40 trials of English, 40 trials of Mixed, and 40 trials of Visual, were summed up to one set of experiments. The researchers performed the overall three sets of experiments in sequence for each subject as illustrated in Table 2. The language and visual conditions were randomly mixed among themselves in a sequence for each subject. This gave us the overall 120 trials for each language and visual condition for one subject. The subject could ask for a break between sets, conditions, or whenever and for however long they needed.

Table 2

Example of experimental sets, trials, and sequence for a research subject

Experiment						
Set 1		**Set 2**		**Set 3**		**Overall number of Trials**
Sequence	**Number of Trials**	**Sequence**	**Number of Trials**	**Sequence**	**Number of Trials**	
English	40	English	40	English	40	120
Thai	40	Thai	40	Thai	40	120
Visual	40	Visual	40	Visual	40	120
Mixed	40	Mixed	40	Mixed	40	120

The sequence in each set of experiments was randomly assigned to each subject, so all the subjects did not start at the same condition and follow the same sequence.

Data analyses

Correlation analysis was employed to examine the relationship between the manipulation performance across the visual and auditory tasks. If WM manipulation is domain-general and is thus shaped by bilingual experience in a similar way across linguistic and non-linguistic domains, the positive correlation between the behavioral performance in manipulating the WM contents across the visual and verbal tasks will be observed.

Statistical analyses

Six data analysis methods are employed. First, Analysis of Variance (ANOVA) is used. Variance is the dispersal of the data points around the mean. ANOVA is a collection of statistical models used to analyze differences among means when comparing means of several datasets. A two-way ANOVA is used to analyze the effects of two categorical independent variables on a continuous dependent variable. It allows researchers to determine whether there are significant interactions between the independent variables and whether each independent variable has a significant main effect on the dependent variable. ANOVA produces *F*-statistic or *F*-value, which is the ratio between two variances (between-group variance and within group variance). *F*-value is reported in the form of *F*(d.f.). Degree of freedom (d.f.) is the number of all subjects minus 1. Larger *F*-value (and lower *p*-value, $p < 0.05$) signifies that the result is significant because there is higher variation between sample means than variation within the samples. Second, post-hoc *t*-tests are used to carry out multiple *t*-tests to test for differences between each pair of categories. Post-hoc *t*-tests are used as a follow-up to ANOVA to determine which comparison pair contributes to the overall significant difference observed in the *F*-value.

Third, the Bonferroni correction is used with the post-hoc *t*-tests to adjust the *p*-values to decrease the errors that may arise from making multiple statistical tests. Fourth, regression analysis is used to show the relationship between two variables, one dependent variable against another independent variable, in each pairwise comparison. Fifth, Pearson Correlation Coefficient takes into account the covariance and their standard deviations to yield the correlation coefficient called *rho*, which is a measure of the closeness of the linear relationship between variables on the *x*-axis and *y*-axis. *Rho* values range from -1 to 1. The closer the *rho* value gets to -1, the closer the relationship between variables on the *x*-axis and *y*-axis is a perfect negative linear correlation. The closer the *rho* value gets to 1, the closer the relationship between variables on the *x*-axis and *y*-axis is a perfect positive linear correlation. Last, Bayes factor is used in Bayesian hypothesis testing to quantify the strength of evidence for one hypothesis relative to another. It provides a way to compare the likelihood of observing the data under different competing hypotheses.

RESULTS

Questionnaire results

The LSBQ yields the overall 14 males and 12 females. Given that 1 means no proficiency in that language and 10 means native proficiency in that language, the results from the questionnaire reveal the profile of the subjects as follows: The mean score of Thai proficiency based on their rating is 9.12, *S.D.* ±1.19. The mean score of English proficiency based on their rating is 5.99, *S.D.* ±1.76. The mean age of all the subjects is 25.96, *S.D.* ±5.63. Table 3 below shows the average age the subjects began learning Thai and English. The subjects are classified as sequential and subordinate because they started learning the second language (English) after the age of three when they already had a strong mother tongue (Thai).

Table 3
Average age the subjects start learning the languages at home and in school

Average age starting learning Thai (year)		Average age starting learning English (year)	
at home	in school	at home	in school
2.54 (±2.62)	5.00 (±2.86)	5.42 (±2.33)	6.04 (±2.13)

Figure 3 shows the number of subjects in each language proficiency level. The histogram suggests that the subjects are relatively homogeneous, native Thai speakers with different English language proficiency levels (Figure 4).

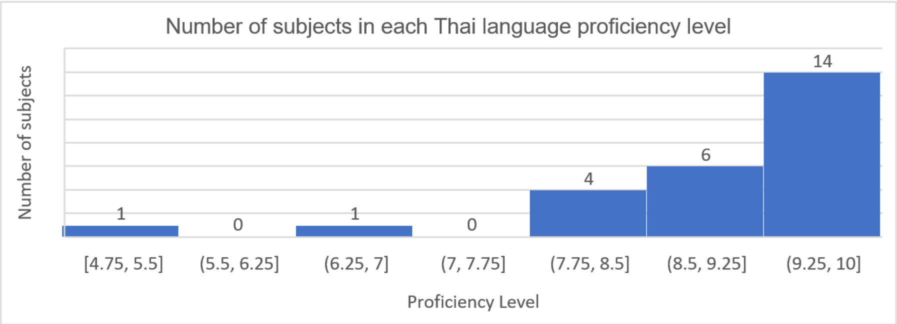

Figure 3 The number of subjects in each Thai language proficiency level

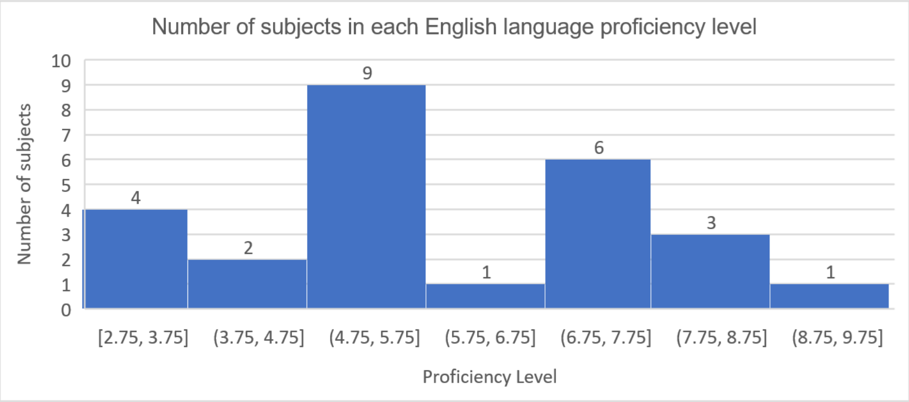

Figure 4 The number of subjects in each English language proficiency level

Behavioral results

All the subjects significantly outperformed the chance levels (0.160% for each language task, 0.800% for visual task) of getting the entire letter sequence correct for both maintenance and manipulation conditions. The WM manipulation effect on hit was computed by subtracting hit rates of the maintenance condition from the hit rates of the manipulation condition in English, Mixed, Thai, Visual tasks. Regression analyses reveal that WM manipulation effect on hit correlates significantly among the language tasks, English-Thai ($rho(1, 25) = 0.581$, $p = 0.002$), English-Mixed ($rho(2, 25) = 0.577$, $p = 0.020$), and Thai-Mixed ($rho(3, 25) = 0.390$, $p = 0.049$, Figure 5), but does not correlate significantly between the language tasks and the visual task, English-visual ($rho(1, 25) = 0.202$, $p = 0.323$), Mixed-visual ($rho(1, 25) = 0.159$, $p = 0.439$), Thai-visual ($rho(1, 25) = 0.167$, $p = 0.416$, Figure 6).

The WM manipulation effect on RT was computed by subtracting RTs of the maintenance condition from the RTs of the manipulation condition in English, Mixed, Thai, Visual tasks. Regression analyses reveal that WM manipulation effect on RT correlate significantly among the language tasks, English-Thai ($rho(1, 25) = 0.590$, $p = 0.002$), English-Mixed ($rho(2, 25) = 0.467$, $p = 0.016$), and Thai-Mixed ($rho(3, 25) = 0.551$, $p = 0.004$, Figure 7), but does not correlate significantly between the language tasks and the visual task (English-visual ($rho(1, 25) = 0.247$, $p = 0.225$), Mixed-visual ($rho(1, 25) = -0.059$, $p = 0.776$), Thai-visual ($rho(1, 25) = 0.331$, $p = 0.098$; Figure 8).

Bayes Factor (BF_{10}) reveal that WM manipulation effect on hit rates across the language tasks and the visual task are BF_{10} Mixed-Visual = 0.32 (substantial evidence for the null hypothesis) and BF_{10} Thai-Visual = 0.33, BF_{10} English-Visual = 0.39 (anecdotal evidence for the null hypothesis). Bayes Factor reveal that WM manipulation effect on RTs across the language tasks and the visual task are BF_{10} Mixed-Visual = 0.25 (substantial evidence for the null hypothesis) and BF_{10} Thai-Visual = 0.89, BF_{10} English-Visual = 0.49 (anecdotal evidence for the null hypothesis). See Appendix B for Bayes Factor Interpretation.

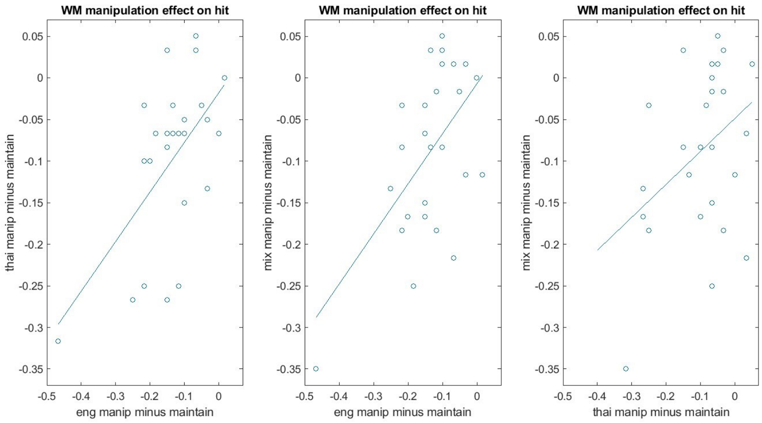

Figure 5 WM manipulation effects on hit rate, comparing correlation across the language domain ($p \leq 0.05$ (*), $p \leq 0.01$ (**), $p \leq 0.001$ (***), $p > 0.05$ (not significant))

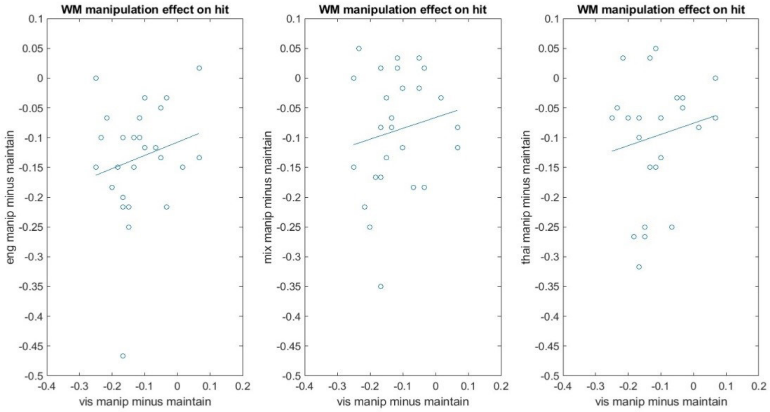

Figure 6 Correlations of WM manipulation effect on hit across the language and visual domains ($p \leq 0.05$ (*), $p \leq 0.01$ (**), $p \leq 0.001$ (***), $p > 0.05$ (not significant))

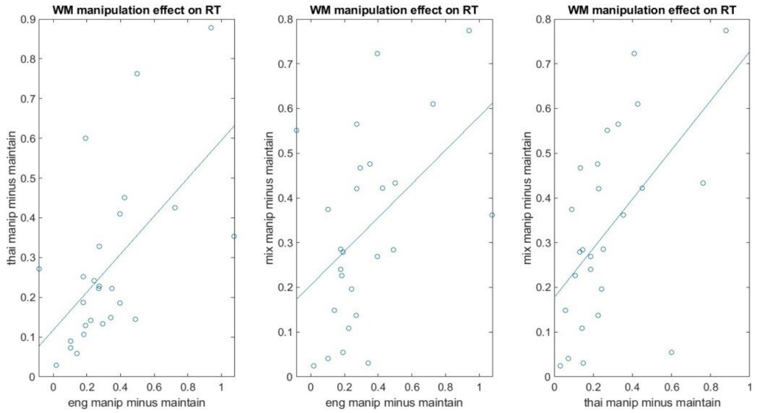

Figure 7 WM manipulation effects on reaction time (RT), comparing correlation across the language domain ($p \leq 0.05$ (*), $p \leq 0.01$ (**), $p \leq 0.001$ (***), $p > 0.05$ (not significant))

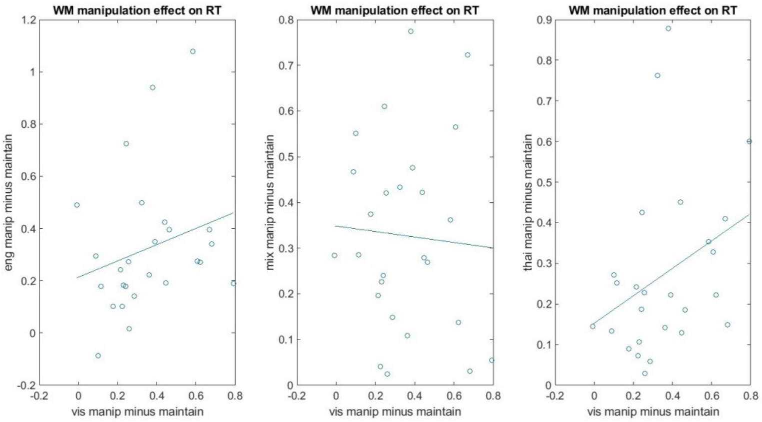

Figure 8 Correlations of WM manipulation effect on reaction time (RT) across the language and visual domains ($p \le 0.05$ (*), $p \le 0.01$ (**), $p \le 0.001$ (***), $p > 0.05$ (not significant))

Correlations between English language proficiency and WM manipulation effect in the language tasks and the visual tasks are not significant, English-English proficiency (*rho*(1, 25) = 0.007, *p* = 0.974), Mixed-English proficiency (*rho*(2, 25) = -0.010, *p* = 0.963), Thai-English proficiency (*rho*(1, 25) = -0.121, *p* = 0.556), Visual-English proficiency (*rho*(1, 25) = -0.044, *p* = 0.830; Figure 9). Similarly, correlations between age and WM manipulation effect in language tasks and the visual tasks are not significant, English-age (*rho*(1, 25) = -0.178, *p* = 0.383), Mixed-age (*rho*(2, 25) = -0.128, *p* = 0.533), Thai-age (*rho*(1, 25) = -0.113, *p* = 0.583), Visual-age (*rho*(1, 25) = 0.282, *p* = 0.163; Figure 10).

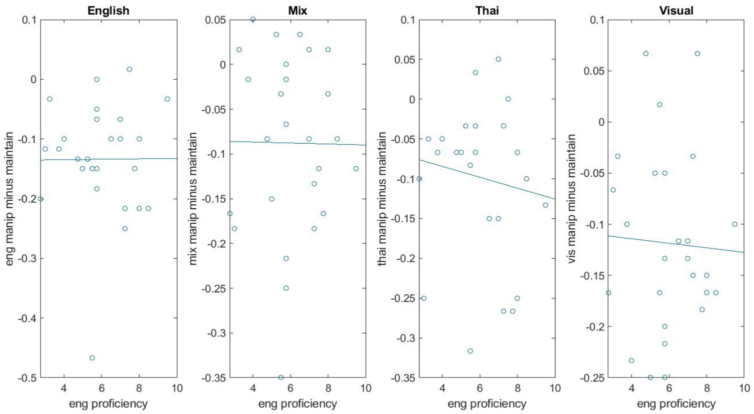

Figure 9 Correlations between English proficiency and manipulation effect across the language domain ($p \le 0.05$ (*), $p \le 0.01$ (**), $p \le 0.001$ (***), $p > 0.05$ (not significant))

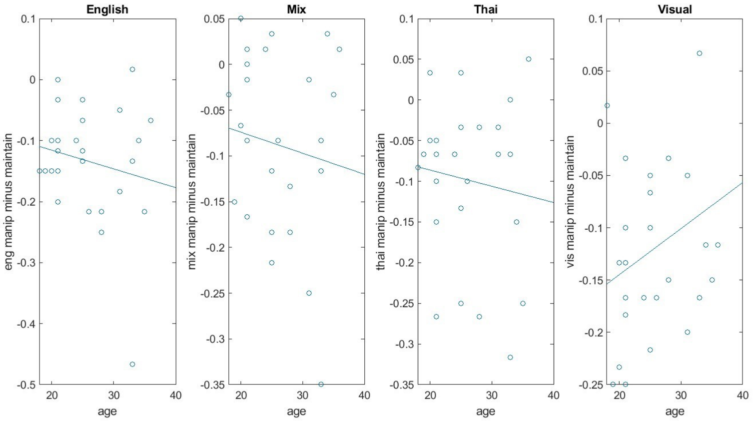

Figure 10 Correlations between age and manipulation effect across the language domain ($p \leq 0.05$ (*), $p \leq 0.01$ (**), $p \leq 0.001$ (***), $p > 0.05$ (not significant))

Also, the hit rates in the English, Mixed, Thai, and Visual tasks are significantly lower in the manipulation condition than in the maintenance condition as shown in the two-way ANOVA ($F(25) = 44.50$, $p < 0.001$; Figure 11). Consequently, the RT in the English, Mixed, Thai, and Visual tasks are significantly higher in the manipulation condition than in the maintenance condition ($F(25) = 68.51$, $p < 0.001$).

The hit rates differ significantly among the language tasks ($F(25) = 32.15$, $p < 0.001$). Post-hoc *t*-tests (Bonferroni adjusted *p*-value = 0.017) reveal pairwise comparisons of means contributing to the overall significant difference that is observed in the F-statistic among the language tasks, specifically English-Thai ($t(1, 25) = -6.279$, $p = 0.004$), English-Mixed ($t(2, 25) = -2.400$, $p = 0.024$), and Thai-Mixed ($t(3, 25) = -6.537$, $p = 0.000$). Likewise, the reaction times (RTs) differ significantly among the language tasks ($F(25) = 23.49$, $p < 0.001$). Post-hoc *t*-tests (Bonferroni adjusted *p*-value = 0.017) reveal pairwise comparisons of means contributing to the overall significant difference that is observed in the F-statistic among the language tasks, specifically English-Thai ($t(1, 25) = 5.077$, $p = 0.000$), English-Mixed ($t(2, 25) = 1.150$, $p = 0.000$), and Thai-Mixed ($t(3, 25) = 5.393$, $p = 0.000$).

Thus, Thai has a higher hit rate than Mix and Mix has higher hit rate than English while English has higher RT than Mix and Mix has higher RT than Thai.

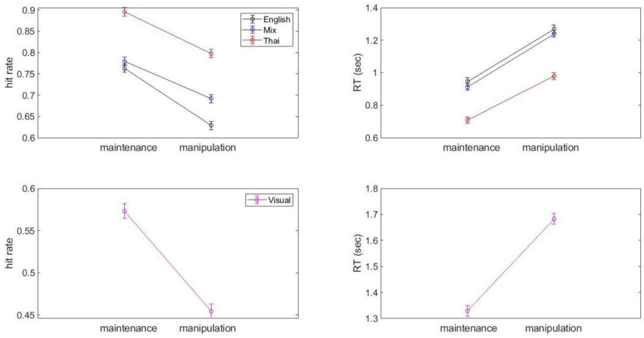

Figure 11 Comparison between the maintenance and manipulation conditions of hit rate (Left) and reaction time (RT, Right) among the English, Mixed, Thai (Top) and visual (Bottom) tasks

DISCUSSION

It is hypothesized that (1) there are correlations in the WM manipulation effect on behavioral data (hit rate and RTs) between languages (Thai, English, Mixed). (2) There are correlations in the WM manipulation effect on behavioral data (hit rate and reaction time) between the language (Thai, English, Mixed) and visual domains. Supporting the first hypothesis, the results show that the WM manipulation effects of hit rates and RTs correlate between each language pairwise, suggesting that Thai-English bilingual adults use the same cognitive mechanism that supports WM manipulation across languages, or within the linguistic domain.

The hit rates and RTs correlate among the language tasks with post-hoc *t*-tests confirming pairwise comparisons (English-Thai, English-Mixed, Thai-Mixed) of means contributing to the overall difference that is observed in the *F*-statistic among almost all the language tasks. The regression analyses confirm linear relationship between each of the language pairwise comparisons. The WM manipulation effect on hit in a language task correlates with that of the other language tasks. When the subjects perform one language task in the manipulation better than the maintenance conditions, they will do so in the other language tasks.

However, the results refute the second hypothesis as WM manipulation effects between the language (Thai, English, Mixed) and visual domains do not correlate, suggesting that Thai-English bilingual adults may not use the same cognitive mechanism that supports WM manipulation across the linguistic and verbal domains. The hit rates and RTs do not correlate between the language tasks and the visual task, implying that when the subjects perform one language task in the manipulation better than the maintenance conditions, they will not perform so in the visual task, and vice versa. Bayesian correlation analysis of hit rates and RTs also confirms this lack of correlation across the language tasks and verbal task as it suggests substantial evidence for the null hypothesis in the correlation of WM manipulation effects across the Mixed-Visual tasks, and anecdotal evidence for the null hypothesis in the correlations of WM manipulation effects across the Thai-Visual and English-Visual tasks (see Appendix B: Bayes Factor Interpretation).

There might be a trend toward correlation across the linguistic and visual domains, but from our behavioral results, the cognitive transfer cannot be generalized across these domains. These results are consistent with the literature showing that cognitive transfer between the visual and verbal domains is possible by means of neuroplasticity, but there are many factors influencing this far transfer that may limit it including the individual's belief in the malleability of the brain and the cognitive trainings the individuals have received (Dahlin et al., 2008; Kray & Ferdinand, 2013).

WM manipulation effect on hit rates of the three language tasks as well as the visual task do not correlate with English language proficiency level, implying English proficiency level does not affect hit rates in the subjects with low (1-5) and high (6-10) proficiencies. The WM manipulation effect on hit rates of the three language tasks as well as the visual task do not correlate with age, implying that age does not affect hit accuracy in the younger (18-26) and older (27-36) subjects. These results are consistent with other studies reporting that L2 proficiency and age do not affect WM manipulation in the subjects in this age range (Crone et al., 2006; Emery et al., 2008).

Results show that hit rates in the manipulation conditions are lower than the maintenance conditions, reflecting the greater level of difficulty it takes to complete the manipulation tasks as cognitive loads increase (Albouy et al., 2017; Itthipuripat et al., 2013; Sauseng et al., 2005). All the subjects outperformed the chance levels of getting the entire letter sequence correct for both maintenance and manipulation conditions, suggesting that they paid attention to doing the tasks, not simply guessing the answers.

LIMITATIONS AND FUTURE DIRECTIONS

There are two main limits in this study. First, the English task may not resemble the real cognitive demand that bilinguals face in everyday life since the English (L2) words used in this study are one-syllabic and frequently-used words e.g., dog, cat, and bee. These words are carefully selected for this study to control for the different L2 proficiency levels in the subjects. The researchers would like to compare the WM manipulation effects within the verbal domain, and between the visual and verbal domains. Thus, it is imperative that every subject understand the meaning of all the L1 and L2 words used in the study so that the results obtained are not due to the difficulty of words. The words that are specific to any particular field of study are avoided. Also, the words in each language should match in length and number of syllables.

Since frequency of use is a vital factor influencing the speed at which bilinguals successfully access and retrieve the meaning of words from their memory, future studies should incorporate the more advanced and infrequently-used L2 words that are carefully controlled to match with the Thai words in meaning, length, and syllable, e.g., ยา-drug, ศาล-court, ท่อ-pipe, to study the effects of word difficulty and L2 proficiency on WM manipulation effects within the verbal domain, and between the visual and verbal domains.

Second, the pool of subjects available in our Bangkok area is limited mostly to the Thai-English sequential bilinguals who begin learning English as a second language after the age of three. It is difficult to clearly observe patterns from the results and make implications from this pool of subjects, but future studies can be extended to include Thai-English simultaneous bilinguals and compare their WM manipulation effects in the behavioral data with those of the Thai monolingual subjects. Also, neuroscientific technique such as EEG can be used to subserve the behavioral results.

PEDAGOGICAL IMPLICATIONS

Nowadays, not all Thai adults are Thai-English bilinguals, but are being encouraged to be. To encourage the learners to learn foreign vocabulary which will enhance their English proficiency, the teachers can train the learners using the linguistic tasks that focus on manipulation of contents in their working memory (WM). Also, the fact that the learners can be trained across different languages suggests that this WM manipulation task can be used for the third language or used in the first language, so the learners can transfer this strategy to learning new languages as well.

Our results show that the cognitive trainings are possible, but only within the linguistic domain. The manipulation effect can be trained across different languages using linguistic tasks, but the visual task may not produce the desired manipulation effect in the verbal tasks. Educators and teachers should use linguistic manipulation tasks to teach students when they wish them to get better at the same task in another language. In the Multi-component WM Model (Baddeley, 2012; Baddeley & Hitch, 1974), the phonological loop in WM provides an active storage for students to learn unfamiliar words (e.g., foreign words) and learn to associate these words with their meanings, visual images, contexts, or words that they have already learned. When capacity and efficiency of the phonological loop are greater, the vocabulary size (in the long-term memory) is greater, the verbal fluency is better, and the speed of acquiring foreign vocabulary is faster.

To train for an efficient phonological loop, teachers can design to use Thai only, English only, or the combination of both as our results show that all of these three language conditions significantly correlate with one another. However, they should keep in mind that the manipulation is more difficult than the maintenance of language contents such as words and phrases. English manipulation condition is more difficult than the Mixed manipulation condition, and the Mixed manipulation condition is more difficult than the Thai manipulation condition for native Thai adults. If teachers wish to design a cognitive training program for Thai adult students with low English proficiency level, it is recommended that they start from the easy conditions and gradually move to the more difficult ones in order to progress along the Zone of Proximal Development.

For example, in the Mixed-manipulation, the students heard a sequence of words e.g., “นก (bird), room, ship, ผึ้ง (bee)”. After a musical note, a new word “cat” appears. The students manipulate the sequence in their WM into “room, ship, ผึ้ง (bee), cat” before they responded by sequentially choosing the pictures corresponding to the meaning of each word.

Williams (1999) suggests that limitation in short-term memory capacity might put a limit on a person’s organization and use of linguistics knowledge. Training the students on the cognitive tasks that combine the WM training with linguistic training such as introduction of new L2 words into the Mixed task in both maintenance and manipulation conditions can help students enhance both the WM capacity and the words’ forms and meanings. Visual representations such as pictures that signify the meaning of these new L2 words can be incorporated into the training tasks. Students with low L2 proficiency tend to rely on the frontal control network to process L2 contents, but with enough time and training, their L2 proficiency levels reaches automaticity level, and they change from the reliance on the frontal control network to the subcortical and posterior brain regions. This provides bilingual benefits as it frees the frontal control network to do other cognitively demanding tasks and reserves cognition because the frontal area of the brain tends to deteriorate faster than the posterior areas in old age (Bice et al., 2020).

Ideally, it is advised that students learn their L2 by both living or immersing themselves in an environment where that L2 language is used frequently on a daily basis, and learning their L2 through explicit instructions in a classroom at the same time. This combination would target both the implicit and explicit memories of the students, leading them to automaticity in L2 faster and in a more natural manner. Unfortunately, many Thai students have difficulty finding such a natural environment where English is used on a daily basis. Thus, explicit learning in classroom and linguistic cognitive trainings can be alternatives that put them onto a path to L2 automaticity as well.

CONCLUSION

This study answers the main question of whether human cognitive control can be generalized across linguistic and non-linguistic domains. Though there has been much debate on the subject, our behavioral results indicate that WM manipulation effects correlate significantly within the linguistic domains i.e., English and Thai, English and Mixed, Thai and Mixed, but not between the linguistic domain and the visual domain. English (L2) proficiency level and age do not contribute significantly to the WM manipulation effects observed in each verbal and visual task. Important implications for cognitive trainings are presented in favor of the training programs targeting the linguistic WM tasks using different languages and task conditions. Future works should focus on incorporating advanced words that more resemble the real-world language use and include the Thai-English simultaneous bilinguals into the experiment.

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Appendix A

แบบประเมินประวัติทางภาษา (ไทย-อังกฤษ)

ข้อมูลติดต่อ
ชื่อ-นามสกุล: ________________________ อีเมล: ________________________

เบอร์โทรศัพท์: ________________________ วันที่ทำแบบประเมิน: ________________________

กรุณาตอบคำถามต่อไปนี้ตามความเป็นจริง โดยใส่เครื่องหมาย ☐ หรือเติมคำตอบในช่องว่าง

๑. อายุ (ปี): _______________

๒. เพศ: ☐ ชาย ☐ หญิง

๓. อาชีพ: ____

๔. ระดับการศึกษาสูงสุด: ____

๕. ระยะเวลาที่เคยใช้ชีวิตอยู่ในต่างประเทศที่ใช้**ภาษาอังกฤษ**เป็นภาษาหลัก (ในการทำงาน และการใช้ชีวิตประจำวัน)

____________ปี____________เดือน

๖. เป็นเวลาผ่านมาแล้วกี่ปีในครั้งล่าสุดที่ท่านใช้ชีวิตในต่างประเทศ

____________ปี____________เดือน

๗. ภาษาใดที่ท่านเรียนรู้เป็นภาษาแรก (หากท่านเติบโตมาโดยเรียนรู้ภาษามากกว่า 1 ภาษาพร้อมกัน โปรดระบุ)

☐ อังกฤษ ☐ ไทย

๘. ท่านเริ่มเรียน**ภาษาอังกฤษ**เมื่ออายุเท่าใด (ปี)

เริ่มเรียนที่บ้าน _______ เริ่มเรียนที่โรงเรียน _______

๙. ท่านเริ่มเรียน**ภาษาไทย**เมื่ออายุเท่าใด (ปี)

เริ่มเรียนที่บ้าน _______ เริ่มเรียนที่โรงเรียน _______

๑๐. ท่านใช้ภาษาไทยและภาษาอังกฤษอย่างละประมาณกี่เปอร์เซ็นต์ต่อวัน (รวมทุกกิจกรรมของวัน)

ภาษาไทย _______% ภาษาอังกฤษ _______%

๑๑. ท่านมักจะทำกิจกรรมต่อไปนี้ในภาษาใด

บวก/ลบ/คูณ/หารเลขคณิตศาสตร์	☐ ภาษาอังกฤษ	☐ ภาษาไทย
ฝัน	☐ ภาษาอังกฤษ	☐ ภาษาไทย
แสดงความโกรธหรือความรัก	☐ ภาษาอังกฤษ	☐ ภาษาไทย

๑๒. เมื่อเปรียบเทียบความสามารถในการใช้ภาษาอังกฤษของท่านกับเจ้าของภาษา ท่านมีความสามารถด้าน ต่าง ๆเหล่านี้ใน **ภาษาไทย**มากเท่าใด (๑ คือไม่มีความสามารถด้านนี้เลย และ ๑๐ คือมีความสามารถด้านนี้สูงเทียบเท่าเจ้าของภาษา)

พูด _______
เข้าใจ _______
อ่าน _______
เขียน _______

๑๓. เมื่อเปรียบเทียบความสามารถในการใช้**ภาษาอังกฤษ**ของท่านกับเจ้าของภาษา ท่านมีความสามารถด้าน ต่างๆ เหล่านี้ใน **ภาษาอังกฤษ**มากเท่าใด (๑ คือไม่มีความสามารถด้านนี้เลย และ ๑๐ คือมีความสามารถด้านนี้สูงเทียบเท่าเจ้าของภาษา)

พูด _______
เข้าใจ _______
อ่าน _______
เขียน _______

๑๔. ท่านใช้**ภาษาไทย**มากเท่าใดในแต่ละกิจกรรมต่อไปนี้

	ไม่ใช้	น้อย	ปานกลาง	มาก	ทั้งหมด
พูด	☐	☐	☐	☐	☐
ฟัง	☐	☐	☐	☐	☐
อ่าน	☐	☐	☐	☐	☐
เขียน	☐	☐	☐	☐	☐

๑๕. ท่านใช้**ภาษาอังกฤษ**มากเท่าใดในแต่ละกิจกรรมต่อไปนี้

	ไม่ใช้	น้อย	ปานกลาง	มาก	ทั้งหมด
พูด	☐	☐	☐	☐	☐
ฟัง	☐	☐	☐	☐	☐
อ่าน	☐	☐	☐	☐	☐
เขียน	☐	☐	☐	☐	☐

๑๖. เมื่อท่านสนทนากับผู้อื่น ท่านเคยผสมคำหรือประโยคระหว่างภาษาไทยและภาษาอังกฤษในบทสนทนาครั้งเดียวหรือไม่

☐ เคย ☐ ไม่เคย

หากเคย ท่านผสมคำหรือประโยคระหว่างภาษาไทยและภาษาอังกฤษในบทสนทนาครั้งเดียวบ่อยครั้งแค่ไหน

☐ น้อยครั้ง ☐ บางครั้ง ☐ บ่อยครั้ง ☐ ทุกครั้ง

ขอบคุณสำหรับความร่วมมือ

Language and social background questionnaire (English-Thai)

Contact Information:

Name: ______________________ Email: ______________________

Telephone: ______________________ Today's Date: ______________________

Please answer the following questions to the best of your knowledge by putting a ☐ in the boxes or write answers in the space provided below.

1. Age (in years): ___________ 2. Sex: ☐ Male ☐ Female

3. Occupation: ____

4. Highest level of education: ____

5. Specify the duration of your stay in the country that uses **<u>English</u>** as the main language (at work and in daily life)

______________ year(s) ______________ month(s)

6. Specify the number of years (and months) that has passes since your last stay abroad?

______________ year(s) ______________ month(s)

7. Specify the language you learn first in your life (If you grew up with more than one language simultaneously, please specify)

☐ English ☐ Thai ________________________________

8. Please specify the age at which you started to learn the **<u>English</u>** language in the following situations (in years)

At home _________ At school _________

9. Please specify the age at which you started to learn the **<u>Thai</u>** language in the following situations (in years)

At home _________ At school _________

10. Estimate the percentage you use English and Thai languages per day (in all daily activities):

English _________% Thai _________%

11. In which languages do you usually:

Add, multiply, and do simple arithmetic?	☐ English	☐ Thai
Dream?	☐ English	☐ Thai
Express anger or affection?	☐ English	☐ Thai

12. Relative to a highly proficient speaker's performance, rate your proficiency level on a scale of 0-10 for the following activities conducted in **English** (1 means no proficiency at all and 10 means native-like proficiency).

Speaking	_______
Understanding	_______
Reading	_______
Writing	_______

13. Relative to a highly proficient speaker's performance, rate your proficiency level on a scale of 0-10 for the following activities conducted in **Thai** (1 means no proficiency at all and 10 means native-like proficiency).

Speaking	_______
Understanding	_______
Reading	_______
Writing	_______

14. Of the time you spend engaging in each of the following activities, how much time is carried out in **Thai**?

	None	Little	Some	Most	All
Speaking	☐	☐	☐	☐	☐
Listening	☐	☐	☐	☐	☐
Reading	☐	☐	☐	☐	☐
Writing	☐	☐	☐	☐	☐

15. Of the time you spend engaged in each of the following activities, how much time is carried out in **English**?

	None	Little	Some	Most	All
Speaking	☐	☐	☐	☐	☐
Listening	☐	☐	☐	☐	☐
Reading	☐	☐	☐	☐	☐
Writing	☐	☐	☐	☐	☐

16. When you are speaking, do you ever mix words or sentences between English and Thai?

☐ Yes ☐ No

If yes, how often do you ever mix words or sentences between English and Thai?

☐ Rarely ☐ Sometimes ☐ Frequently ☐ Always

THANK YOU FOR YOUR COOPERATION

Appendix B

Bayes factor interpretation

Interpretation of Bayes factors (BF_{10}) as evidence for null hypothesis (H0) and alternative hypothesis (H1). BF_{10} indicates the Bayes factor in favor of H1 over H0, whereas BF_{01} indicates the Bayes factor in favor of H0 over H1 (Adapted from Jeffreys, 1961; Van der Linden et al., 2018).

In the present study, the null hypothesis refers to not having significant correlations in WM manipulation effect of hit rates and RTs across the verbal and visual domains, while the alternative hypothesis refers to having significant correlations in WM manipulation effect of hit rates and RTs across the verbal and visual domains.

Bayes factor (BF_{10})	**Evidence Category**
<0.01	Decisive evidence for H0
0.03–0.01	Very strong evidence for H0
0.10–0.03	Strong evidence for H0
0.33–0.10	Substantial evidence for H0
0.33–1	Anecdotal evidence for H0
1	No evidence
1–3	Anecdotal evidence for H1
3–10	Substantial evidence for H1
10–30	Strong evidence for H1
30–100	Very strong evidence for H1
>100	Decisive evidence for H1