# The Modulation Effect of Bilingualism on Implicit Learning in Aging Adults

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The Asian Conference on Psychology & the Behavioral Sciences 2026
Official Conference Proceedings

**Abstract**

Implicit learning enables individuals to acquire complex patterns without conscious awareness (Reber, 1967). Although generally preserved across the lifespan, older adults often show reduced performance when tasks involve complex sequences. Bilingualism may provide a protective advantage against age-related cognitive decline (Bialystok, 2011; Stern, 2009). The present study examined whether bilingualism modulates implicit learning ability in aging adults using two experiments with the nonverbal Serial Reaction Time (SRT) task (Nissen & Bullemer, 1987) with simple and complex visual sequences. Participants included 48 younger bilingual adults (aged 18–25; Cantonese–English), 51 older bilingual adults (aged 65–75; Cantonese–English), and 49 older monolingual adults (aged 65–75; Cantonese only). Results showed no implicit learning effects among younger adults, likely due to ceiling performance. Monolingual older adults showed slower responses over time, reflecting fatigue, whereas bilingual older adults showed significant improvement across blocks in the complex-sequence condition ($\beta = -9.43$, $p = .009$), indicating successful implicit learning. These findings demonstrate that bilingualism provides cognitive benefits beyond deliberate control, extending to unconscious detection of complex patterns and supporting flexible, adaptive learning in aging populations.

*Keywords:* bilingualism, implicit learning, aging, cognitive reserve, serial reaction time task

# Introduction

Population aging has become an increasingly prominent demographic phenomenon, with substantial implications for public health and social welfare. In Hong Kong, the proportion of people aged 65 or above was 1.45 million (19.6% of the total population) in 2021, and this figure is projected to increase to 2.52 million (33.3%) by 2039 (Census and Statistics Department, 2020, 2022). Cognitive decline in aging adults manifests as difficulties in memory, attention, and decision-making, posing significant threats to individual safety and imposing substantial costs on healthcare systems. Therefore, identifying factors that may preserve cognitive abilities in aging adults has become an important area of research.

Among the cognitive processes affected by aging, implicit learning, is of particular interest. Implicit learning refers to the process of learning in which learners learn new information or mastering new skills without conscious intention or deliberate effort (Reber, 1967). Implicit learning underlies a wide range of everyday activities, including perception, language acquisition, motor skill development, and decision-making (Cleeremans et al., 1998). Research on age-related changes in implicit learning has yielded mixed findings: while simple implicit learning tasks appear to be relatively well preserved across the lifespan (Howard & Howard, 1992; Midford & Kirsner, 2005; Rieckmann & Bäckman, 2009), complex implicit learning tasks that require the detection of higher-order statistical regularities show age-related decline (Howard & Howard, 2013; Howard et al., 2004; Vandenbossche et al., 2014). This selective vulnerability of complex implicit learning to aging raises important questions about the mechanisms that might protect or enhance this ability in older adults.

One potential factor that may modulate implicit learning in aging is bilingualism. Bilingualism refers to the ability to comprehend and produce speech in two languages. It has been associated with enhanced executive functions, including cognitive flexibility, inhibitory control, and task-switching (Bialystok, 2011; Bialystok & Barac, 2013; Costa et al., 2008; Diamond, 2010; Gold et al., 2013; Green, 1998). It has been further theorized that lifelong bilingual experience contributes to cognitive reserve, enabling individuals to cope more effectively with age-related neural deterioration (Stern, 2002, 2009). The present study aimed to investigate whether bilingualism can protect implicit learning ability in aging adults, particularly for complex tasks that are most susceptible to age-related decline.

# Literature Review

## Implicit Learning and Aging

Implicit learning refers to the process through which individuals acquire knowledge of underlying regularities in the environment without conscious intention (Reber, 1967). This form of learning is typically assessed using tasks such as the Serial Reaction Time (SRT) task (Nissen & Bullemer, 1987), in which participants respond to sequentially presented stimuli that follow a hidden pattern. Improvements in reaction time across blocks of sequenced trials, relative to random trials, serve as the primary index of implicit learning (Cherry & Stadler, 1995).

The relationship between aging and implicit learning is complex and task-dependent. Previous research has demonstrated that simple forms of implicit sequence learning are relatively preserved in older adults (Howard & Howard, 1992; Midford & Kirsner, 2005; Murray & Prashad, 2025). For example, using standard SRT tasks with simple repeating sequences, older

adults typically demonstrate learning effects comparable to those of younger adults. However, when the statistical structure of the task becomes more complex, significant age-related decline in performance is observed (Howard & Howard, 2013; Thompson et al., 2004; Murray & Prashad, 2025). This pattern has been observed across a variety of complex learning paradigms, including the Alternating Serial Reaction Time (ASRT) task (Howard & Howard, 1997) and probabilistic sequence learning tasks (Vandenbossche et al., 2014).

One proposed explanation for the preservation of simple but not complex implicit learning relates to neural plasticity and compensatory mechanisms. Park and Reuter-Lorenz (2009) demonstrated that older adults recruit bilateral neural activity and exhibit posterior-to-anterior shifts when performing cognitive tasks, reflecting compensatory processes. These compensatory mechanisms appear adequate for simple implicit learning tasks but insufficient for the demands of complex sequence learning (Rieckmann & Bäckman, 2009). Recent neuroimaging research using concurrent transcranial direct current stimulation (tDCS) and functional near-infrared spectroscopy (fNIRS) has further revealed age-specific differences in motor cortex and supplementary motor area involvement during implicit sequence learning, highlighting distinct neural signatures of implicit learning across age groups (Leuk et al., 2025).

**Bilingualism and Cognitive Benefits**

To switch swiftly between two languages, when a bilingual speaker uses one language (e.g., L1), the irrelevant language (L2) must be actively suppressed through inhibitory control (Bialystok et al., 2004; Green, 1998). Furthermore, switching between languages in conversation engages task-switching abilities, while maintaining representations in both languages places a high demand on working memory (Bialystok et al., 2009; Soveri et al., 2011). These ongoing demands are thought to strengthen executive functions over the lifespan (Miyake et al., 2000).

Empirical evidence supports the bilingual advantage in executive functioning. Bilinguals demonstrate faster response times and reduced interference in tasks requiring inhibitory control, such as the Simon task (Bialystok et al., 2004), reduced switching costs in task-switching paradigms (Prior & MacWhinney, 2010), and superior working memory performance (Bialystok et al., 2014). A meta-analysis by Adesope et al. (2010) further confirmed that bilingualism is associated with increased attentional control, metalinguistic awareness, and metacognitive awareness. Recent research by Manica et al. (2026) found that bilinguals outperformed monolinguals in cognitive flexibility, inhibitory control, and working memory, with medium effect sizes.

Nevertheless, findings across studies have been mixed. A large-scale study by Nichols et al. (2020; N = 11,000) found no differences between bilinguals and monolinguals in executive functions, and Zahodne et al. (2014) argued that bilingualism's protective effect was not associated with dementia conversion or reduced rates of decline in executive functions. These mixed findings suggest that the bilingual advantage may be modulated by specific factors such as language proficiency, frequency of language use, and the cognitive domains assessed (Calvo et al., 2016).

**Bilingualism as Cognitive Reserve**

Cognitive reserve (Stern, 2002, 2009) provides a theoretical framework for understanding how bilingualism may modulate age-related cognitive decline. Cognitive reserve refers to individual

differences in the efficiency and adaptability with which cognitive and neural systems are recruited to cope with age-related changes or neuropathology. Experiences that require sustained demands on cognitive control processes, such as education, occupational complexity, and bilingualism, are thought to contribute to the accumulation of cognitive reserve over the lifespan.

Bilingualism has been consistently associated with enhanced attentional and executive control across the lifespan (Bialystok et al., 2014). Previous studies suggest that bilingualism may be associated with a delayed onset of dementia symptoms by approximately four to five years (Alladi et al., 2013; Bialystok et al., 2007), highlighting its potential relevance for cognitive aging. The sustained effect of bilingualism is made possible by the flexible adaptation of the human brain. Arce Rentéria et al. (2019) demonstrated that active bilingualism buffered the impact of age-related cortical thinning on semantic memory in older Hispanic adults, providing evidence for a compensatory mechanism against aging. Grant et al. (2014) proposed an integrative framework linking bilingual experience to cognitive control, cognitive reserve, and brain reserve in aging. Converging neuroimaging evidence further supports this account, showing structural adaptations associated with bilingualism. For example, Abutalebi et al. (2015) reported greater gray matter volume in the anterior cingulate cortex of bilinguals relative to monolinguals, while more recent work by Peitz et al. (2025) identified increased gray matter volume in the subicular complex of the hippocampal formation, with this reserve-related effect persisting across the lifespan.

### The Present Study

Although bilingualism has been widely linked to executive functioning and cognitive reserve, fewer studies have examined whether bilingualism is associated with preserved implicit learning ability in aging adults. Previous research shows that complex implicit learning requires executive resources that could be enhanced by bilingual experience, and that bilingualism contributes to cognitive reserve that may buffer against age-related decline, it is plausible that bilingualism could serve to preserve complex implicit learning in older adults. The present study addresses this issue through two experiments.

Experiment 1 examined age-related differences in implicit learning across simple and complex SRT task conditions in younger and older bilingual adults. It was hypothesized that (1a) older adults would show comparable performance to younger adults in the simple task, and (1b) older adults would show poorer performance in the complex task, reflecting age-related decline. Experiment 2 examined whether bilingualism modulates complex implicit learning in older adults by comparing bilingual and monolingual older adults on the complex SRT task. It was hypothesized that bilingual older adults would demonstrate stronger implicit learning effects than monolingual older adults.

## Methodology

### Participants

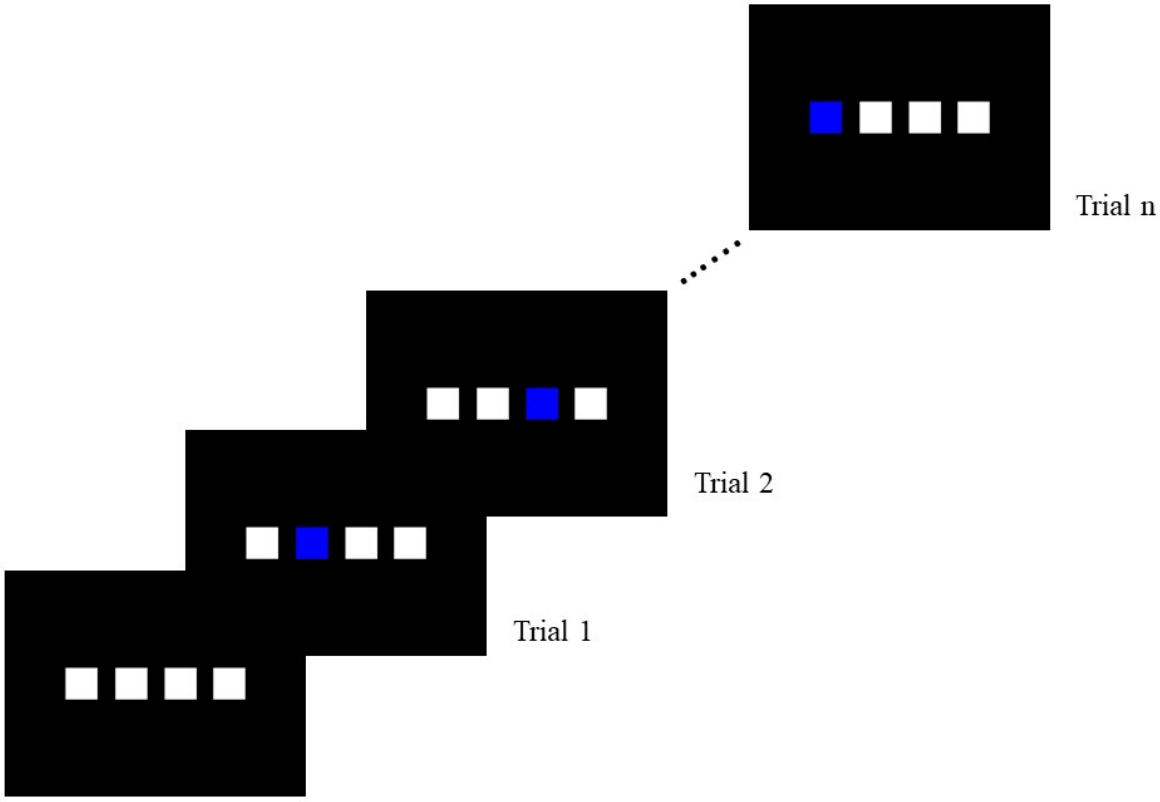
A total of 148 participants were recruited for this study: 48 younger bilingual adults (aged 18–25; Cantonese–English), 51 older bilingual adults (aged 65–75; Cantonese–English), and 49 older monolingual adults (aged 65–75; Cantonese only). Bilingualism was defined as the ability to comprehend and/or produce speech in both Cantonese and English. Language experience and proficiency were assessed using the Language Experience and Proficiency Questionnaire

(LEAP-Q; Kaushanskaya et al., 2020; Marian et al., 2007). Monolingual participants were defined as those who could only comprehend and produce speech in Cantonese. All participants had normal or corrected-to-normal binocular vision and were physically and mentally healthy.

## Materials

The Serial Reaction Time (SRT) task (Nissen & Bullemer, 1987; adapted from Cherry & Stadler, 1995) was used to measure implicit learning. In this nonverbal task, participants responded to the spatial location of a target stimulus appearing in one of four positions on a computer screen by pressing the corresponding key as quickly and accurately as possible (Figure 1). The use of a nonverbal task is to ensure that any group differences could not be attributed to verbal ability differences between bilingual and monolingual participants.

**Figure 1**
*Non-verbal Serial Reaction Time (SRT) Task (Nissen & Bullemer, 1987; adapted from Cherry & Stadler, 1995)*




Task complexity was manipulated through the statistical structure of the sequential rule governing target positions, yielding two conditions.

### *Simple Task (Low-Load Condition)*

The sequential rule consisted of several repetitions of location subsequences (e.g., "2 3 2 4 1 2 4 3 2 4"; Cherry & Stadler, 1995, p. 386), making the underlying pattern relatively easy to extract through repeated exposure.

### *Complex Task (High-Load Condition)*

The sequential rule contained fewer repeating subsequences (e.g., "2 3 2 4 1 2 1 3 1 4"), requiring greater cognitive effort to detect the underlying pattern. Participants were not informed of any sequential rule in either condition; instead, they were instructed simply to respond as quickly and accurately as possible.

## Procedure

In both experiments, all participants completed a randomized SRT block to establish baseline reaction times. Both the simple (low-load) and complex (high-load) SRT tasks consisted of four experimental blocks. Upon completion, all participants were asked whether they had noticed any patterns or rules in the stimulus sequence.

In Experiment 1, younger and older bilingual adults completed both the simple (low-load) and complex (high-load) SRT tasks, with the order counterbalanced across participants. In Experiment 2, both older bilingual and older monolingual adults completed the complex (high-load) SRT task.

Mean reaction time (RT) was calculated for each block. Implicit learning was indexed by the change in RT across the four experimental blocks within each condition, while controlling for individual differences in baseline RT.

# Results

To evaluate implicit learning performance, regression analyses were conducted for each group within each task complexity condition. The dependent variable was block-level mean reaction time, and predictors of implicit learning included baseline reaction times and block number (i.e., times variable). A significant negative coefficient for the times variable indicates that reaction times decreased across blocks, reflecting implicit learning of the sequential pattern after controlling for individual differences in baseline response speed.

## Age-Related Effects on Reaction Time

Overall, older adults were significantly slower than younger adults across all conditions, consistent with established age-related slowing in processing speed. In the simple task, mean reaction times were 370.27 ms for younger adults, 677.33 ms for monolingual older adults, and 605.31 ms for bilingual older adults. In the complex task, comparable patterns were found, mean reaction times were 359.36 ms for younger adults, 649.97 ms for monolingual older, and 610.15 ms for bilingual older adults. Notably, bilingual older adults were faster than monolingual older adults across both conditions, suggesting a general processing speed advantage associated with bilingual experience.

## Implicit Learning Effects

The results of the regression analyses for each group and condition are summarized in Table 1.

***Table 1***

*Regression Coefficients for Block Number (Times) Predicting Reaction Time Across Groups and Conditions*

| Group | Condition | *β* | *SE* | *t* | *p* |
|---|---|---|---|---|---|
| Younger Bilingual | Simple | –0.91 | 2.40 | –0.38 | .704 |
| Younger Bilingual | Complex | –1.29 | 1.83 | –0.71 | .481 |
| Older Monolingual | Simple | 2.84 | 4.81 | 0.59 | .556 |
| Older Monolingual | Complex | –2.98 | 3.15 | –0.95 | .345 |
| Older Bilingual | Simple | –0.52 | 5.34 | –0.10 | .923 |
| Older Bilingual | Complex | –9.43** | 3.58 | –2.63 | .009 |

*Note.* β = unstandardized regression coefficient for block number (times), controlling for baseline reaction times. ** p < .01.

### *Younger Bilingual Adults*

No significant implicit learning effects were observed among younger bilingual adults in either the simple task ($\beta$ = –0.91, *SE* = 2.40, *t* = –0.38, *p* = .704) or the complex task ($\beta$ = –1.29, *SE* = 1.83, *t* = –0.71, *p* = .481). These non-significant findings likely reflect ceiling effects, as younger adults responded at their fastest speed relatively early in the task, leaving limited room for further improvement across blocks.

### *Older Monolingual Adults*

Older monolingual adults did not demonstrate significant implicit learning effects in either condition. In the simple task condition, the regression coefficient for block number was positive ($\beta$ = 2.84, *SE* = 4.81, *t* = 0.59, *p* = .556), indicating a trend toward increasing reaction times across blocks. This pattern seems to reflect a fatigue effect rather than implicit learning, as these participants progressively slowed down in their responses. In the complex task condition, the coefficient was negative but non-significant ($\beta$ = –2.98, *SE* = 3.15, *t* = –0.95, *p* = .345), indicating no reliable implicit learning effect.

### *Older Bilingual Adults*

Older bilingual adults demonstrated a significant implicit learning effect in the complex task condition ($\beta$ = –9.43, *SE* = 3.58, *t* = –2.63, *p* = .009), with reaction times decreasing by approximately 9.43 ms per block after controlling for baseline speed. This finding indicates that bilingual older adults successfully learned the complex sequential pattern across experimental blocks. In contrast, no significant implicit learning effect was observed in the simple task condition ($\beta$ = –0.52, *SE* = 5.34, *t* = –0.10, *p* = .923), likely because the simple task was easy enough that bilingual older adults quickly reached a high and stable level of performance. The model for the complex task in bilingual older adults explained a substantial proportion of variance ($R^2$ = .87, $F(3, 144) = 319.30$, $p < .001$), suggesting the robustness of the findings.

## Discussion

The present study examined whether bilingualism modulates implicit learning in aging adults, using simple and complex SRT tasks. The findings suggest that bilingual older adults show an advantage in complex implicit learning task compared to their monolingual counterparts. Three

key findings were found: (a) younger adults showed no implicit learning effects due to ceiling performance, (b) monolingual older adults exhibited fatigue effects rather than implicit learning, and (c) bilingual older adults demonstrated significant implicit learning effect in the complex task condition.

**Bilingualism as Cognitive Reserve for Implicit Learning**

The finding that bilingual older adults demonstrated significant implicit learning effect in the complex task, while monolingual older adults did not, extends previous work on the bilingual advantage in executive functions (Bialystok, 2011; Bialystok et al., 2014; Gold et al., 2013) to the domain of implicit learning. This result is consistent with the cognitive reserve hypothesis (Stern, 2002, 2009), which posits that enriched life experiences, including bilingualism, contribute to the efficient and flexible recruitment of neural resources that enable individuals to cope more effectively with age-related cognitive decline. The present findings raise the possibility that the positive effect of bilingualism may extend beyond explicit, deliberate cognitive processes to implicit, unconscious learning mechanisms.

**Selective Age-Related Decline in Implicit Learning**

The pattern of results across conditions is consistent with the selective vulnerability of complex implicit learning to aging (Howard & Howard, 2013; Howard et al., 2004). Younger adults showed no significant implicit learning effects in either condition, likely because the tasks were too easy and performance quickly reached ceiling levels. This interpretation is supported by the fast reaction times observed in the younger adult group (approximately 360–370 ms), leaving minimal room for improvement. These findings are consistent with previous research showing that young adults may reach asymptotic performance rapidly on standard SRT tasks (Meissner et al., 2016).

The fatigue pattern observed among monolingual older adults suggests that task demands may have exceeded the available cognitive resources for this group. This is consistent with the resource depletion model, wherein cognitive tasks that are sustained over time may deplete attentional resources more rapidly in older adults with lower cognitive reserve (Craik & Byrd, 1982). The contrast between the fatigue pattern of the monolingual older adults and the learning pattern of the bilingual older adults in the complex condition may suggest the modulatory role of bilingual experience.

**Executive Function as the Bridging Mechanism**

A plausible mechanism linking bilingualism to preserved complex implicit learning performance involves executive control processes. Complex implicit learning tasks require the simultaneous monitoring of multiple stimulus features and the detection of higher-order statistical regularities, processes that draw upon executive functions, such as inhibitory control, cognitive flexibility, and working memory (Janacsek & Nemeth, 2013). Bilingualism can strengthen these processes through the ongoing demands of managing two language systems simultaneously (Bialystok, 2011; Blumenfeld & Marian, 2011; Manica et al., 2026). The enhanced executive control associated with bilingualism may facilitate the implicit detection of complex sequential patterns, which could place bilingual older adults at an advantage relative to monolingual older adults.

This executive control account is further supported by the observation that bilingual older adults tended to respond faster than monolingual older adults across task conditions, pointing to generally more efficient processing rather than condition-specific effects. Consistent with this interpretation, Gallo et al. (2022) reported that second-language proficiency modulated the association between cognitive reserve and executive performance in healthy older bilinguals, suggesting that bilingual language experience may contribute to a more adaptable cognitive system in later life.

### Cognitive Reserve Hypothesis Revisited

The cognitive reserve theory (Stern, 2002, 2009) proposes that speaking two or more languages helps maintain greater cognitive flexibility through the sustained engagement of neural networks involved in language control. The present findings shed light on the possibility that this protective effect extends from explicit cognitive processes to implicit, unconscious learning mechanisms. This is notable because implicit learning underlies many everyday activities that are critical for independent functioning in older adults, including the acquisition of new routines, adaptation to changing environments, and social cognition (Cleeremans et al., 1998).

Recent evidence from Cardaio and Keijzer (2025) provides converging support for this interpretation, showing that lifelong multilingualism is associated with brain and cognitive reserve through sustained engagement of cognitive control mechanisms from earlier to more advanced stages of Alzheimer's disease. Similarly, Mendoza-Ruvalcaba et al. (2026) reported that cognitive reserve, with bilingualism as a key indicator, accounted for 20.1% of the variance in successful aging among community-dwelling older adults. Taken together, these findings suggest that bilingualism's contribution to cognitive reserve may be broad and relatively robust across cognitive and clinical contexts.

### Limitations and Future Directions

Several limitations should be considered when interpreting these results. First, bilingualism was operationalized using a categorical grouping approach, which allowed for a clear comparison between bilingual and monolingual older adults but did not capture the full range of individual differences in language experience (see Yow et al., 2021). Future research may build on the current findings by incorporating more fine-grained characterizations of bilingual experience to further refine understanding of how language use relates to implicit learning in aging. Second, the study focused on Cantonese–English bilinguals within a specific sociocultural context. Replication across other language environments would be valuable for assessing the broader applicability of the observed patterns. Third, ceiling effects among younger adults limited direct age-group comparisons in the present task, suggesting that tasks with greater difficulty variation may be useful in future work. Beyond healthy aging, an important next step will be to examine whether the observed patterns extend to populations with greater cognitive vulnerability.

## Conclusion

The present study provides novel evidence that bilingualism modulates implicit learning in aging adults. Bilingual older adults demonstrated significant implicit learning in a complex sequential task, whereas monolingual older adults did not, suggesting that bilingual experience may provide a potential protective effect against age-related decline in complex implicit

learning. These findings extend the bilingual advantage literature beyond executive functions and explicit cognitive processes to encompass implicit, unconscious learning mechanisms, and are consistent with the cognitive reserve hypothesis. These findings have theoretical implications for understanding the relationship between bilingualism, cognitive reserve, and implicit learning, and may also inform future efforts to develop language-based approaches to support cognitive health in aging populations.

## Acknowledgements

The work described in this paper was fully supported by the Hong Kong Metropolitan University research grant (Project Ref. No. PFDS/2021/05).

## Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The author declares that ChatGPT and Co-Pilot were used in proofreading and refining the language used in the manuscript. The usage was limited to correcting grammatical and spelling errors and rephrasing statements for accuracy and clarity. The author further declares that no other AI or AI-assisted technologies have been used to generate content in writing the manuscript. The ideas, design, procedures, findings, analyses, and discussion are originally written and derived from careful and systematic conduct of the research.

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