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Pain, Posture, and Perception: Investigating the Role of Bodily Primes in Placebo Analgesia

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ABSTRACT

Most studies on placebo mechanisms rely on Expectancy Theory, which suggests that conceptual expectations can bring about physiological change. However, the exact processes underlying this effect remain unclear. Perceptual Symbol Systems (PSS) Theory, grounded in Embodied Cognition Theory, offers a more specific explanation: mental representations grounded in sensory-motor systems may directly evoke bodily responses. This study tested whether embodied primes, based on PSS Theory, elicit stronger placebo responses than traditional expectancy-based suggestions. Using a within-subjects design, 71 university students underwent a cold pressure task under three conditions: (1) verbal suggestion of an analgesic cream, (2) visual priming with a photo of a person looking upward, and (3) combined visual-motor priming, where participants also looked upward themselves. The placebo response was measured by changes in pain intensity and heart rate. Results showed that both embodied conditions (visual and visual-motor priming) produced stronger placebo responses than the verbal suggestion condition, as indicated by lower pain intensity and reduced heart rate ($F(2,140)=5.83$; $p<.01$). However, the difference between the two embodied conditions was not statistically significant in terms of pain ratings. Notably, visual-motor priming led to a greater reduction in heart rate than visual priming alone ($F(6,330)=1.99$; $p=.06$), suggesting a subtle additive effect of motor engagement. These findings support the role of unconscious embodied processes specifically, perceptual and motor representations in modulating placebo responses. They offer a promising direction for understanding how non-verbal bodily cues may influence the complex perception of pain.

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Introduction

In the scientific literature, self-healing processes are commonly viewed as a form of *Placebo Response* (Alling, 2015). Most of the models describing this response (except for classical conditioning) consider the individual's awareness to be an essential factor during the experience of a treatment. . Healing as a response to a therapeutic intervention on the biological or psychological level would only occur when the patient is aware of the received treatment (Benedetti, Maggi, Lopiano, Lanotte, Reinero, Vighetti, & Pollo, 2003; Miller & Kaptchuk, 2008; Price, 2015).

Expectancy Theory as a comprehensive model explaining the placebo response is rooted in cognitive approaches highlighting the importance of the patient's awareness of receiving the treatment and introduces *verbal suggestions/information* as a key element in initiating the placebo response (Di Blasi, Harkness, Ernst, Georgiou, & Kleijnen, 2001; Stewart-Williams & Podd, 2004). For example, in a series of placebo analgesia studies in patients with Irritable Bowel Syndrome (IBS) (Price, 2015; Craggs, Price & Robinson, 2014; Vase, Norskov, Petersen & Price, 2011) a verbal suggestion was used telling patients they would receive pain analgesia shown to be effective. Placebo effects were higher in patients who received this verbal suggestions compared to those who did not (Craggs et al., 2014; Vase et al., 2011). Brain activity was compared between groups by MRI, and results indicated that only the group receiving the verbal suggestion showed a significant decrease in brain activity for pain perception (Craggs et al., 2014).

Apparently, awareness of receiving a treatment plays a key role in initiating placebo responses, and, thereby, likely self-healing processes and increases treatment effectiveness. However, recent approaches in cognitive sciences, including Embodied Cognition Theory (ECT), suggest that self-healing processes in the body can potentially be initiated without any accompanying conceptual or verbal message (Leitan, Williams & Murray, 2015). According to ECT, no explicit expectation or thought is necessary in order to induce a healing process. Cognitive and affective processes are situated in physical context (e.g. bodily posture and movement) (Barsalou, 1999; Leitan et al., 2015; Frenkel, 2008).

Perceptual Symbols Systems (PSS; Barsalou, 1999) theory a subset of ECT, suggests a model in which concepts, such as healing, are "modal" representations. By activating a concept via priming cues (e.g. a straight and upward posture), "simulation" of that concept can be initiated as a neural reconstruction of its experience in modal centers of the brain (Barsalou, 1999); simulation, in turn, may then be realized on a behavioral level (e.g. subjective pain relief).

Recent research in cognitive science examined the claims proposed by PSS. Leitan et al. (2015) used the priming paradigm for the embodied investigation of the healing response. In this experimental study, after priming the concept of healing by using an associated symbol (i.e. upright posture and looking upward), participants were asked to classify words as either healing-related or unrelated. Results indicated that participants responded faster to healing-related words than to unrelated words. Using the same priming technique, Leitan (2013) showed that observing healing symbols (Leitan, 2013; Leitan et al., 2015) visually may activate the embodied concept of healing resulting in perceptual changes (e.g. pain relief). Researchers introduced posing a straight bodily state as a proper behavioral way for pain and tension resilience (Michalak, Mischnat, & Teismann, 2014; Michalak, Troje, Fischer et al., 2009).

Nair, Sagar, Sollers, Consedine, & Broadbent (2015) showed that in a stressful experimental environment, priming an upright posture may result in increased self-esteem and motivation, improved attitude and reduced fear comparison to a slumped posture. Moreover, the results indicated that those who assuming a slumped posture tended to use more negative emotional words, more first person singular pronouns, and less positive emotional language. Furthermore, following embodied priming of the concept of "power" psychological tensions was significantly reduced (Nair, Sagar, Sollers, Consedine & Broadbent, 2015; Hung & Labroo, 2011). Other similar studies showed that even holding a "painkiller" medication--as a symbol of healing--in one's hand may increase pain tolerance and reduce perceived pain intensity (Rutchick & Slepian, 2013). Also, based on PSS theory, the perceptions, actions, proprioceptions, introspections and emotions which happen during the processing of a concept can be considered as "embodiments" of that concept (Barsalou, 1999; Leitan et al., 2015). This claim is supported with the study of Valentini, Martini, Lee, Aglioti & Lannetti (2014) which showed visual exposure to facial expressions of positive emotions (which usually occur simultaneously with pain relief) has been shown to enhance analgesic placebo effects (Valentini, et al., 2014).

Embodied approaches may make use of a powerful interaction between sensorimotor and cognitive systems outside of conscious cognition (Balcetis & Cole, 2009). What distinguishes this theory from traditional cognitive theories is the notion that somatic experiences can affect or even induce psychological states and, as a result, influence behavior (Barsalou, 1999; Barsalou, Niedenthal, Barbey, & Ruppert, 2003). All aforementioned processes occur independent of conscious awareness and may serve as support of an alternative explanations of placebo responses. However, there is a lack of research comparing embodied priming and verbal suggestion for placebo analgesia. The aim of the current study is to investigate the effectiveness of embodied priming of a healing symbol compared with a verbal suggestion on the response to a placebo intervention for pain. The research question was: does embodied priming using a healing symbol (upright bodily posture) induce a stronger placebo response compared to a verbal suggestion?

Method

Setting and Participants

Undergraduate students (N = 88) of Tehran University were invited to participate in the study. Participants were screened for any physical injury or recent disease (heart-disease, diabetes, Reynaud disease, extreme blood pressure, epilepsy, and arthritis) or acute or chronic pain conditions in hand/wrist, or neck, pregnancy, and for taking any pain medications on the day of the experiment. Subjects with any of these conditions were excluded in order to reduce risks and biased results. Thirteen students were excluded because they rated their average pain as ≤ 3 when taking their hands out of the cold water. As a result, data of 71 participants (44 female, 27 male) were analyzed for pain intensity. Among these, the heartbeats of 56 individuals were recorded using Photo plethysmography (PPG).

Experimental Design and Procedures

We conducted a within-subject study using three experimental conditions: (a) verbal priming to receive a treatment shown to be effective (placebo analgesia), (b) priming using a visual healing symbol, or (c) visual-motor priming using the healing symbol and applying a symbolic healing posture. We assessed perceived pain intensity and stress arousal by heart rates at four time points. The three experimental conditions were assigned in random order.

Cold-pressor. To induce pain on the subject's right hand, a standard cold-pressor device was used. Water temperature was set to 6 C°. A water pump secured constant-temperature cold water flow through the tank with a built-in thermostat, thermal sensors, and digital display (Chemia Rahavard Company, 2013).

Physiological evaluation of heart rate. To assess the heart rate, an electrode was placed on the middle finger of the subject's left hand. Heartrate data were registered by a computer using Khaje-Nasir Modern Technologies Company (VER2013) software.

Placebo cream. An inactive cream was used described to participants as an analgesic topical cream. Both participants and the research assistant were blind to its lack of activity.

Numeric Rating Scale (NRS). Perceived pain during the experiment was assessed by the Numeric Rating Scale representing the level of pain (Jensen, Karoly, O'Riordan, Bland, & Burns, 1989). The scale consists of pain rating on a scale from 0 (no pain) to 10 (maximum pain). The level of perceived pain intensity was verbally indicated by the participants and recorded by the research assistant.

Procedure

Participants signed informed consent. The whole procedure was explained to the subject, and he would have the chance to ask questions. To reduce the novelty effect, subjects were exposed to the test procedure before the assessments and asked to place their hand in the cold water and remain at the position until the pain is no longer bearable; then, the hand was taking out of water. After 5 minutes of rest the experiments were conducted.

Participants underwent three experimental conditions which took about one hour. Before cold-pressure exposure, they were asked to rate their baseline pain if any. This was followed in random order by: healing induction by visual priming, visual-motor priming, and verbal suggestion. Time interval between conditions was 5 minutes. However, if after this interval subjects rated their pain intensity as more than 1, the interval was extended until they rated pain intensity as 0.

In visual priming condition, participants were sitting at a table facing a white wall, on which the visual stimuli were projecting, while the research assistant stood behind them. The digital thermostat showed the temperature of the water in the center of the container as 6 C$^{\circ}$.

According to perceptual symbols system theory, reaching the concept of *healing* could be related to activation of embodied simulations of that concept (Barsalou et al., 2003). That is, embodied visual priming of healing, like a straight posture, can trigger the simulation of healing concept when there is a need to heal (for example while experiencing pain), and therefore, results in healing.

Moreover, using motor priming in accordance with visual priming could increase the chance for reaching the simulated concept, and as a result would enhance the probability of feeling healed on a behavioral level (Simmons & Barsalou, 2003). For example, posing an upright gesture, in addition to a visual priming of straight posture when there is a need to heal (like while feeling pain), is expected to increase the chance for reaching the healing concept, and enhance the feeling of being healed.

In each three conditions, participants were instructed to place the right hand down to the wrist into the water with his fingers extended without touching the container walls. The NRS scale of pain intensity was projected onto the wall, and participants were asked to rate their pain at the first immersion. Pain ratings were recorded by a research assistant, who was unaware of the experimental conditions and their purposes. The subjects would keep their hands in the water until the pain was no longer bearable. From the initial pain rating to the moment of taking the hand out of water, subjects kept looking at the projected visual healing symbol (described below). Immediately after exiting the hand, subjects would place it on the table, and rate pain intensity again with four subsequent ratings every 30 seconds between rating participants were asked to look at the presented visual stimuli.

Visual Priming Condition: Based on Leitan et al. (2015), the stimulus provided in the visual priming condition was an image of an upright standing person looking upwards. The stimulus was projected onto the center of the screen, and subjects were asked to focus on the image, and not to look around. The gender on the image matched that of the subject (Figure 1).

Visual-Motor Priming Condition: The same visual stimulus was used again in the visual-motor priming condition. In addition participants were asked to move their head to look upwards.

Verbal Suggestion Condition: Subjects were told that "a medical company sponsoring our study asked us to evaluate the effectiveness of an analgesic topical medicine as part of our experiments. We are putting this cream on your hand before you place it in the water". In the verbal condition only, participants were asked to look at a Celtic cross) projected on the wall in front of them.

Heartrates were recorded continuously using the PPG sensors.

Following the experiments, subjects were appreciated and debriefed. Participants were informed of the general purposes and were promised to receive more detailed information and the results at an upcoming seminar. At the Psychology and Educational Sciences Faculty of the Tehran University.

Data screening and statistical analysis

Setting time periods for healing from pain severity and feeling of pain: Before applying the analyses, 5 variables related to pain severity, at the moment of, and at 30, 60, 90, and 120 seconds after taking the hand out of cold water, transformed to variables of subjective pain healing. Since our goal was to evaluate pain relief after taking the hand out of water, the rating differences of time periods of 30, 60, 90, and 120 seconds with the hand-exiting moment were calculated. This results in four variables representing the level of healing from the moment that the hand was out of water to each of these time periods. Four variables of relief from pain severity includes, pain severity from hand-exiting moment to 30 seconds after that, from hand-exiting moment to 60 seconds after that, from hand-exiting moment to 90 seconds after that, and pain severity from hand-exiting moment to 120 seconds.

By the means of PPG records, the same method was used to calculate the heart rate healing. That is the heart signals of each subject over 5 time-periods were extracted, and by the same calculations 4 heart-rate healing values ultimately were heart rate healing from hand-exiting moment to 30 seconds after that, from hand exiting moment to 60 seconds after that, from hand-exiting moment to 90 seconds after that, and heart rate healing from hand-exiting moment to 120 seconds after that.

To investigate the effect of experimental conditions (intra-subject comparison) on pain severity and heart rate, repeated measures of ANOVA was used. Statistical analyses were done using SPSS-16 software.

Figure 1. Posing a straight looking upwards gesture as an embodied visual-healing symbol (Leitan et al., 2015)

Results

Data analysis for 13 participants reporting pain severity of less than 3 when taking their hands out of cold water was omitted reducing the sample to 71 subjects. Heart rate data were available for 56 subjects.

Means and standard deviation of pain intensity and heartrate for the three conditions are presenting on Table 1.

Table 1 Mean and SD for Pain Intensity and HR for three Conditions; Comparisons between the conditions using Repeated-measures of ANOVA

Dependent Variables	**Condition**	**Means and standard deviations**				**Condition Effect**	**Conditions*time Effect**
		30 sec*	60sec	90sec	120sec	F-value (df), p-value	F-value (df), p-value
Healing as indicated in pain intensity (VAS) (N=71)	Verbal Suggestion (1)	2.92 (1.53)	4.76 (2.69)	5.59 (3.11)	5.96 (3.33)	5.831 (2, 140), p<.01	.91 (6, 420), p=.48
	Visual Priming (2)	3.34 (1.99)	4.99 (1.97)	5.94 (2.02)	6.36 (2.07)		
	Visual-Motor Priming (3)	3.33 (1.77)	5.28 (1.77)	6.16 (1.84)	6.50 (1.90)		
Healing as indicated in Heart Signals (N=56)	Verbal Suggestion (1)	.40 (1.53)	.84 (2.69)	.95 (3.11)	1.05 (3.33)	.55 (2, 110), p=.57	1.99 (6, 330), p=.06
	Visual Priming (2)	.65 (2.10)	.86 (2.46)	.95 (2.89)	.92 (3.42)		
	Visual-Motor Priming (3)	.44 (1.87)	1.02 (3.01)	1.40 (3.38)	1.56 (3.60)		

* Time interval after hand removal from cold water

Repeated Measures of ANOVA analysis showed that there were differences between three condition in pain intensity ratings (F (2, 140) = 5.83; p<.01). Pairwise comparisons showed a difference between the average of pain severity at visual-motor condition and expectation condition (p< 0.001) which was found to be in favor of the visual-motor condition. Expectation condition revealed a less average healing than visual condition (p<0.05), however, no difference was found between visual and visual-motor conditions in pain intensity relief (p=0.29).

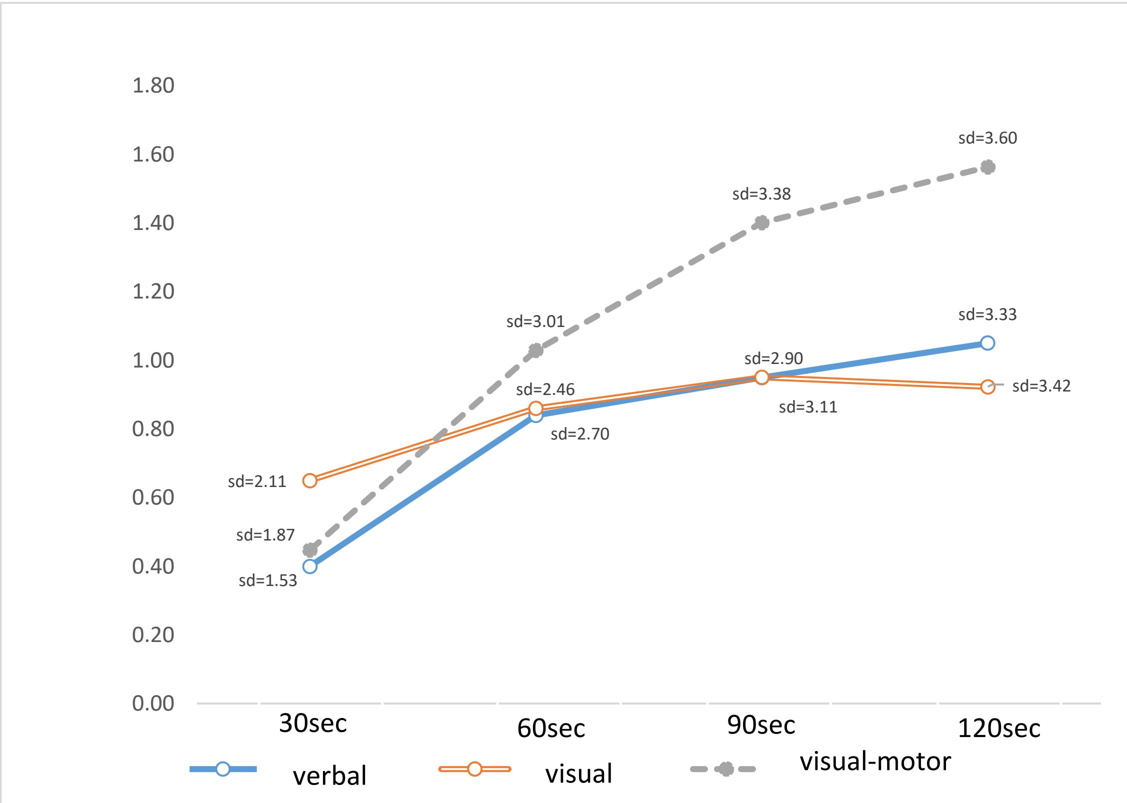

Figure 2. Heart-rate healing at three conditions of expectation, visual, and visual-motor conditions

Figure 2 shows over time (1.99 (6, 330), p=.06) (table 1) the effect of visual-motor priming becomes superior in inducing healing as reflected in heart rate signals.

Discussion and Conclusion

The results in line with previous studies (Kaptchuk, 2002; Miller & Kaptchuk, 2008) indicate that the pain relief were dependent on context, in our case depending on priming conditions with the embodied visual-motor priming having a pain intensity reducing effect superior to, using verbal suggestion. Furthermore, adding the motor modality to the visual modality (visual-motor condition), in comparison to the effectiveness of visual modality (alone), only was shown to be effective in reducing the heart rate signals, and the subjects reported no difference between visual and visual-motor priming conditions in the level of healing from pain intensity.

In summary, we studied the effects of verbal suggestion compared to embodied priming on pain relief following the cold pressure test. The results indicate a general difference between experimental conditions: visual-motor condition more effective than visual condition and expectation condition in pain relief following coldpressor test. In all of these conditions the subject would experience an ease of pain, however, for causing this, the visual-motor condition is found to be more effective than visual condition and visual condition than expectation condition regarding pain intensity healing. Though visual-motor priming could ease the pain more than visual priming, when compared, there was no significant difference considering reduction of the pain severity. Heart-rate signals reduction also seems to follow the same pattern at three conditions but it does show a considerable difference between healing through visual condition and visual-motor condition especially on final time-periods (60, 90, and 120 seconds) of the experiment.

According to Perceptual Symbols System (PSS) Theory, posing an upright posture (as a healing symbol) while experiencing pain would initiate the simulation of healing concept on a behavioral level (Barsalou et al., 2003), reflected in the reports of pain severity and heart-rate index, supported by experimental studies (Leitan et al., 2015). In addition, based on PSS theory, using more modalities can initiate a more powerful simulation of a concept when compared to single modality and this would be reflected on a behavioral level. Therefore, we studied the visual modality alone, and its combination with motor modality, and then compare the findings. According to the results, by activating the simulation of healing concept, it is likely that a healing symbol (placebo) unconsciously play an important role in pain relief. Pain alleviation in visual-motor condition supports the claim that relief could be bodily and unconsciously manipulated. However, embodied induction of healing at visual condition was less effective than at combined condition of visual-motor, and visual priming alone, was not sufficient enough to make embodied priming more effective than verbal suggestion in order to induce healing state, Pain is a complex experience which includes physical, cognitive and emotional dimensions (Hirsch & Liebert, 1998). Neurologically, these dimensions relate to different parts of the brain. Although pain reduction levels in visual-motor condition compared to visual-condition was not statistically different, however, in the case of heart-rate regulation, these two conditions indicate a considerable and almost significant difference at some certain time periods. As shown earlier, the two conditions had similar pattern of reduction at the first seconds of taking the hand out of water. However, over the time up to 120 seconds, the differences between these conditions get higher. It seems adding motor modality to visual modality for activation of healing concept is not effective enough to make a difference between the two priming conditions considering making change to the level of pain. It is possible that visual modality functions better in the activation of healing concept than motor modality, therefore adding the latter may enhance the perception of relief, but it does not make a significant difference at the physical perception of pain reduction. Although there is no separate evaluation of the effectiveness of motor modality alone in this study, implicitly it could be concluded that visual priming can be sufficient enough to initiate simulation of the healing concept. The result may indicate that the modalities have different power in the process of concept simulation and its manifestation on behavioral level.

Latter finding support the notion that an unconscious simulation process may affect the perceived pain response. Based on the Perceptual Symbols System, the findings show this process can be clear on a conscious level of (perceived pain intensity) and its probable effect is on an unconscious neural level (which was reflected in heart-rate signals) (Benedetti, Carlino, & Pollo, 2011; Wager, 2005). As a result, the neural effect can enhance the perceived pain mitigation on a physical-sensory and heart-rate level. However, to support this interpretation additional studies are essential.

An alternative explanation could be that a straight gesture along with looking upwards may distract individuals from pain, as it has been shown that distraction from pain can successfully reduce pain (Van Ryckeghem et al. 2011). Another explanation could be that a straight body-gesture along with looking upwards may activate self-concepts such as pride, strength, and positive emotions, which may directly or indirectly affect the experience of pain (Leitan, 2013). Studies have shown that the position of head could manipulate the feelings of pride and positive emotions (Stepper & Strack, 1993), which, in turn, may affect the perception of pain (Berges, Seale & Ostir, 2011). Further research is needed to disentangle context effects from these potential mediators.

The results of this study support the role of embodied cognition and unconscious processes in producing pain relief responses. Placebo response may be produced in conscious ways in accordance with expectancy theory and unconsciously with embodied approaches (e.g. PSS). Our findings support the role of embodied mechanisms in the placebo response. This is consistent with Teasdale (1994), who suggests motor manipulations can function as an effective psychological treatment, and presenting straight body-gesture would help with the process of physical and psychological well-being.

The results of the current study should be considered along with its limitations. First, the current study had a relatively small sample size. Moreover, the sample of the study was selected from university students so the results cannot be generalized to other non-clinical or clinical samples (e.g. pain patients). Another method to strengthen the data would be to provide between-condition effect sizes with SD. Finally, study sample was selected from a non-patient population, and the results need to be evaluated in future studies, by studying a population of individuals who experience acute or chronic pain.

Declarations

Author Contributions

All authors contributed actively to the conception, design, and execution of the research.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Ethical considerations

All procedures performed in studies involving human participants were in accordance with the ethical standards of University of Tehran research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Ethic approval has been obtained before conducting the research.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this research.

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Is it Possible to Learn Complex Implicit Tasks, Such as Artificial Grammars, While Mind Wandering?

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ABSTRACT

This study examined whether individuals can implicitly acquire rule-based knowledge, such as in artificial grammar learning (AGL), while mind wandering. Implicit learning occurs without conscious awareness, and AGL tasks provide a well-established method for investigating this process. In the current experiment, 116 undergraduate participants memorized 23 grammatical letter strings across 10 training blocks. Between blocks, thought probes assessed the extent of mind wandering. In the subsequent testing phase, participants judged 32 novel strings as grammatical or nongrammatical. Results showed that participants performed significantly above chance in classifying grammatical items, indicating successful implicit learning of the underlying structure. A Bayesian correlation analysis revealed no significant association between self-reported mind wandering and classification accuracy ($r = .04$), with a 95% confidence interval of [-.14, .22] and a Bayes Factor of $B01 = 12.78$, supporting the null hypothesis. These findings suggest that implicit learning is resilient to attentional fluctuations and can occur even when cognitive resources are partially disengaged. While mind wandering often disrupts tasks requiring executive control, it did not impair AGL performance. Instead, the results align with theories emphasizing the automatic, unconscious nature of implicit learning. Overall, the findings highlight the robustness of implicit learning mechanisms and extend understanding of how cognition operates under conditions of reduced attention.

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Introduction

Implicit learning, an important aspect of human cognition, is the process of learning without awareness of an underlying stimulus and without the intention of learning (Gerth, Münte, & Rüsseler, 2006). Implicit learning can be defined as automatically extracting knowledge from the environment without intending to do so and without awareness of what has been learned (Reber, 1967). This phenomenon is a ubiquitous aspect of human cognition, underpinning numerous essential abilities, including language and motor skills.

Importantly, implicit learning may be subject to domain-specific or experience-based constraints or biases which may facilitate or impede the learning of certain kinds of information. For example, implicit learning may be influenced by the complexity of the to-be-learned rule system (Rohrmeier & Cross, 2009), a factor that could be a byproduct of innate predispositions (e.g., Hauser et al, 2002), more general cognitive constraints (e.g., Rey et al, 2012), or the allocation of attention at the time of learning (e.g., Pacton & Perruchet, 2008). This last factor, allocation of attention at the time of learning, is the factor of interest in the current study.

Artificial grammar learning (AGL) has long provided a window into the mechanisms of implicit learning. In a typical AGL paradigm, participants are exposed to letter strings generated by a finite-state grammar and later asked to classify novel strings as grammatical or ungrammatical (Dienes, et al, 1991; Chang & Knowlton, 2004). Despite being unable to articulate the rules of the grammar, participants reliably perform above chance in these classification tasks, indicating sensitivity to structural regularities embedded in the stimulus stream (Pothos, 2007; Seger, 1994). These findings have traditionally been interpreted as evidence that AGL reflects automatic, unconscious learning mechanisms that operate independently of explicit cognitive control. Indirect measures of awareness, or subjective measures of awareness of the rules has also been reported to be evidence for implicit learning (cf. Rebuschat et al, 2015; Sachs et al, 2020; Shanks, 2005).

However, the extent to which AGL is truly impervious to attentional fluctuations remains an open question. While some research suggests that implicit learning is robust under dual-task or divided attention conditions (Frensch et al., 1999; Fu et al., 2010), other studies have reported that reducing attentional resources during learning can impair performance (Leclercq & Seitz, 2012; Jiménez & Méndez, 1999). One factor that has received relatively little empirical attention in the context of AGL is mind wandering—the tendency for attention to drift away from external task demands toward internally generated thoughts (Smallwood & Schooler, 2006). Mind wandering is a pervasive aspect of cognitive life, often occurring without awareness and frequently associated with reduced task performance across a range of domains, including reading comprehension (McVay & Kane, 2012), working memory (Mrazek et al., 2012), and sustained attention (Robertson et al., 1997).

Mind wandering is when thoughts are produced that are unrelated to the goal of completing the current task. Put differently, mind wandering is defined as a shift from an ongoing activity to task-unrelated thoughts (TUTs). These TUTs are extremely common. Extant research suggests that we mind wander 30%-50% of the time (Levison et al, 2012; McVay & Kane, 2012). It is also clear from the extant literature that TUTs typically lead to decrements in performance in the ongoing activity (McVay & Kane, 2009, 2012: Unsworth & McMillan, 2013). Mind wandering is typically measured subjectively in experimental studies. Participants are typically asked to describe or rate their thought content immediately preceding a thought probe briefly interrupts an ongoing primary task (Smallwood & Schooler, 2006; Kane & McVay, 2012).

Smallwood and Schooler (2006) stated that mind wandering demands attentional (executive control) resources. This demand on executive control draws resources away from the task at hand without proper metacognitive monitoring. However, the extant literature has focused on how TUTs impair performance on explicit learning and other tasks in which attentional resources are required.

Given its association with impaired task performance, mind wandering might be expected to interfere with AGL by disrupting the encoding of sequential structure during the exposure phase. However, if AGL reflects an automatic learning mechanism that operates largely outside of conscious awareness, then it may be resilient—even functional—in the face of attentional disengagement. In fact, under some conditions, reduced cognitive control may facilitate implicit learning by minimizing the interference of explicit strategies or hypothesis testing (Cleeremans & Jiménez, 2002). From this perspective, mind wandering may not necessarily be detrimental to learning; rather, it could be orthogonal—or even beneficial—to the acquisition of implicit structure.

The present study tests the hypothesis that participants can learn an artificial grammar even while mind wandering. Using a standard AGL task combined with thought-probe methodology, we measured participants' self-reported attentional states during the exposure phase and examined whether AGL performance (grammaticality classification accuracy) varied as a function of mind wandering frequency. If implicit learning mechanisms operate independently of conscious attention, we should observe above-chance performance even among participants who frequently report mind wandering. Such findings would have implications not only for theories of implicit learning, but also for understanding the boundaries of attention's role in cognitive acquisition.

Method

Participants

116 undergraduates from a large Midwestern University were recruited from the Department of Psychological Sciences participant pool. Participants received course credit for their participation.

Materials and Procedures

Participants completed the experimental task online. The task was programmed using PsychoPy® and administered via Pavlovia.org. Participants were provided the opportunity to compete the research for credits in their course of record and recruitment took place via the department's online participant recruitment system. Once the participant chose to complete the study, they followed a link in the participant recruitment system and were directed to Pavlovia.org to complete the task.

After initially starting the task, participants were presented with a screen prompting them to consent to the experiment. Participants were then prompted to enter their name and course for appropriate credit to be assigned by their course instructor. Participants were deidentified after course credit was awarded.

The experimental task consisted of three components: a training phase, mind-wandering probes, and a testing phase. At the beginning of the experimental task participants were provided instructions for the training phase of the experiment. Participants were instructed that they would be presented with several letter strings that would repeat throughout the experiment. They were told that their task was to do their best to memorize each of the letter strings. Participants were also informed that they would periodically be asked if they are paying attention to the task and to please answer honestly. Participants were not told about the testing phase of the experiment, nor were they informed of the grammatical structure of the letter strings at this point.

Stimuli

The letter strings were constructed using the artificial grammar paradigm from Chang and Knowlton (2004). Following Chang and Knowlton, grammatical strings were generated by starting at the "IN" arrow and picking up a letter while traversing from one state to the next until an "OUT" arrow is reached (see Figure 1). Nongrammatical strings were formed by introducing an error in one position of an otherwise grammatical string. A list of the letter strings used in both training and testing are presented in the Appendix. Letter strings consisted of a minimum of two letters and a maximum of six letters. "XVXJJJ" and "XVT" represent letter sample letter strings.

Training Phase

The training phase stimuli consisted of 23 grammatical strings of letters that were repeatedly presented. A training phase trial began with the presentation of an asterisk in the center of the screen for 500ms. Next, a letter string was presented in the center of the screen and remained for 3000ms before disappearing, followed by a 500ms blank screen. Stimuli were randomly presented in blocks in which each of the 23 stimuli was presented once. Participants were presented 10 blocks for a total of 230 training phase trials. Four mind-wandering probes were pseudo randomly distributed after training phase blocks 3, 4, 6, and 10. Figure 2 represents a block of training phase trials followed by a response probe. These four probes asked the participants where their attention was in that moment on a scale from (1) completely off task to (6) completely on task.

Testing Phase

After the 230 trials and the last mind-wandering probe, participants completed the testing phase of the experiment. During the testing phase, participants were presented 32 new letter strings in random order. One half of the letter strings were constructed to be grammatically correct according to the artificial grammar paradigm and one half were constructed to be ungrammatical. Participants were informed that the sets of letters they were asked to memorize in the training phase were created using a specific set of complex rules and that all previous stimuli followed those rules but, they were not informed about the nature of the rules. Participants were instructed to select 1 for "yes" the new letter string conformed to the rules or 2 for "no" if they believed that the letter string did not match the same set of grammatical rules as the previous 23 strings. Letter strings were preceded by an asterisk for 500ms and again presented in the middle of the screen and remained on the screen until the participant responded. The reminders "1 = Yes" and "2 = No" were presented with the stimuli.

Results

Figure 1 presents the mean proportion correct of testing phase responses by grammaticality (including total mean proportion correct). Mean accuracy for all testing phase items was M = .55 (SD = .10). A two-tailed, single-sample t-test comparing mean accuracy to chance accuracy (.50) indicated that participants were better than chance at determining whether new stimuli in the testing phase were grammatical or ungrammatical, $t(112) = 5.40$, $p < .001$, $M_{Diff} = .05$, 95% CI [.03, .07], d =.51.

To test our hypothesis that artificial grammars can be learned when participants mind wandered, we first calculated the mean of the four mind wandering probes responses for all participants. Participants' mean responses to mind wandering probes was $M = 3.96$ ($SD = 1.20$).

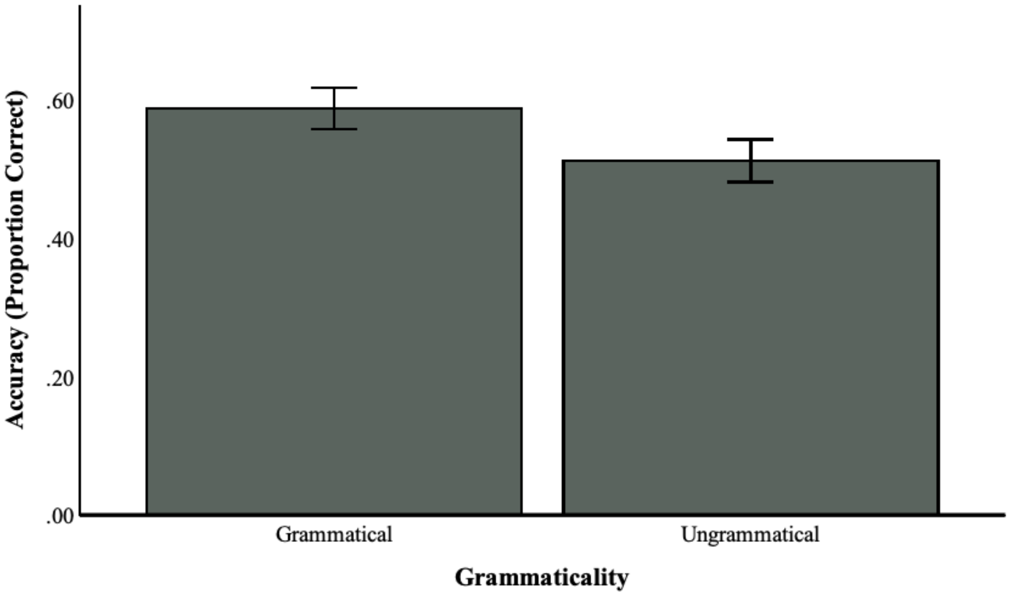

Figure 1. Proportion Correct by Grammaticality

As our hypothesis was that participants would be able to implicitly learn the artificial grammar present in the training phase whether mind wandering or not, we next conducted a Bayesian null correlation analysis to determine if there was no correlation between the amount of mind wandering reported and the proportion of items correctly identified in the testing phase. The Pearson correlation coefficient was not significant, $r = .04$, $p = .66$. The Bayesian analysis revealed a small positive correlation between variable mind wandering probes and accuracy ($r = .04$), with a 95% credible interval of [-.14, .22] and a Bayes Factor of B01= 12.78, indicating substantial evidence in favor of the null hypothesis of no correlation (see Figure 2).

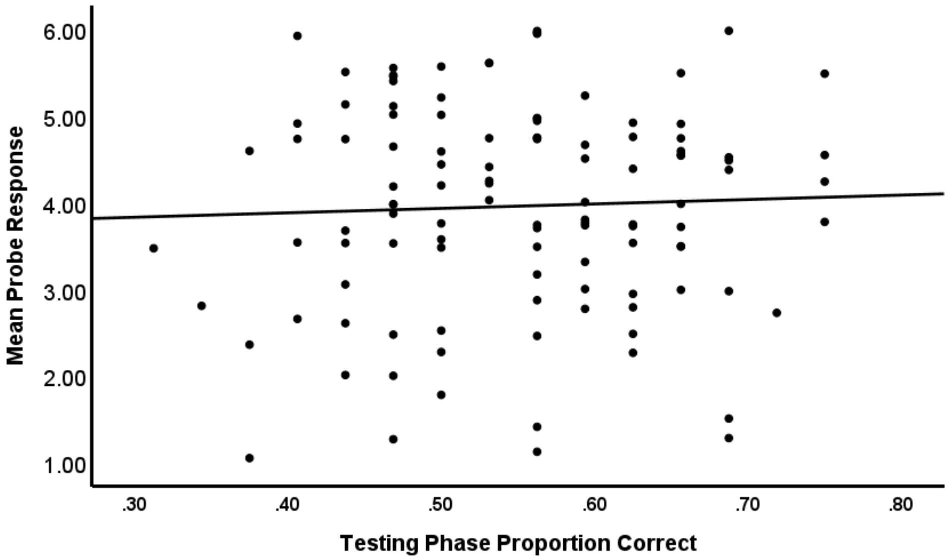

Figure 2. Scatterplot of Mean Probe Response by Testing Phase Accuracy

Discussion and Conclusion

The present study investigated whether participants could implicitly acquire an artificial grammar despite experiencing attentional lapses in the form of mind wandering during learning. Consistent with prior research on artificial grammar learning (AGL), participants demonstrated above-chance accuracy when classifying novel letter strings as grammatical or ungrammatical, even though they were not informed of the rule system during training. Crucially, participants.'

Self-reported frequency of mind wandering during the exposure phase was not significantly correlated with their grammaticality judgment accuracy. Bayesian analysis provided substantial evidence in favor of the null hypothesis, indicating that mind wandering did not impair learning in this context. These findings support the hypothesis that implicit learning mechanisms involved in AGL are resilient to fluctuations in attentional engagement.

This result aligns with theoretical accounts suggesting that implicit learning operates automatically and independently of conscious cognitive control (Reber, 1967; Cleeremans & Jiménez, 2002). While mind wandering is known to disrupt performance in tasks that rely on deliberate attentional regulation, such as reading comprehension or working memory (McVay & Kane, 2012; Mrazek et al., 2012), the current data indicate that these same disruptions may not extend to implicit structure learning. In fact, it is possible that disengaging from external task demands may reduce the influence of explicit hypothesis testing or strategic rule search, thereby preserving—or even facilitating—implicit learning (see Pothos, 2007).

At the same time, the results temper claims that attentional allocation during encoding is necessary for all forms of learning (Jiménez & Méndez, 1999; Leclercq & Seitz, 2012). While attentional resources are critical in many explicit learning contexts, their role in implicit learning may be more nuanced. Our results support the view that implicit learning can occur under conditions of reduced attention, consistent with prior work showing intact learning under divided attention (Frensch et al., 1999; Fu et al., 2010). Extending this literature, the current study is among the first to directly relate trial-by-trial subjective attentional state (i.e., task-unrelated thoughts) to performance on a canonical AGL task.

It is worth noting that while mean performance was significantly above chance, accuracy was relatively modest overall ($M = .55$). This is typical of AGL paradigms in which participants are unaware of the structure and are not instructed to search for patterns. However, the relatively weak magnitude of learning may also reflect a ceiling imposed by the implicit nature of the training and test, or by the potential interference of metacognitive interpretations during the overt classification phase (Hamrick & Sachs, 2018). Notably, participants were alerted at test that the strings had followed specific rules, which may have introduced some degree of strategic guessing or post hoc rule inference. Future studies could assess whether more covert or indirect testing procedures (e.g., forced-choice familiarity or speeded classification without mention of rules; see Zizak & Reber, 2004) yield stronger or more clearly implicit learning effects.

An additional limitation is that mind wandering was assessed using self-report probes distributed across the training phase. While this method is widely used and has good ecological validity (Smallwood & Schooler, 2006; Kane & McVay, 2012), it relies on introspective access to attentional state and may not capture fluctuations occurring between probes. Future work could incorporate physiological or behavioral indices of attentional lapses (e.g., pupillometry, reaction time variability) to triangulate on the moment-to-moment impact of mind wandering on learning.

In conclusion, the present findings contribute to a growing body of evidence suggesting that implicit learning processes can remain intact under conditions of reduced executive attention. Despite high rates of self-reported mind wandering during learning, participants were able to extract and apply grammatical structure from the stimulus stream at levels significantly greater than chance. These findings have important implications for theories of attention and learning, and suggest that even when the mind wanders, the brain may continue to learn.

Declarations

Author Contributions

All authors contributed actively to the conception, design, and execution of the research.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Ethical considerations

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Informed consent was obtained from all participants prior to their involvement in the study

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this research.

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Emotion-specific Sensitivity in an unconscious Facial Perception Task

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ABSTRACT

Emotions are crucial in social interactions, influencing communication and relationships. Distinguishing the perceived emotion in conscious and unconscious emotional processing is a key research area with cognitive and physiological implications. This study investigates conscious and unconscious emotional processing through behavioral and pupillary responses. Participants completed emotion recognition tasks under varying states, revealing higher accuracy in conscious emotion identification. Emotions like anger, happiness, fear, surprise, and neutral elicited distinct response patterns. Pupillometry data showed pupil size suppression in the conscious state and enhancement in the unconscious state, with differences in peak pupil size across emotions. Task-related components, amplitude, and latency parameters differed between conscious and unconscious states, highlighting the role of awareness in emotional regulation. These findings emphasize the complex interplay of cognitive and physiological processes in emotional responses, providing insights into emotional recognition mechanisms. This study contributes to understanding emotional processing dynamics and has implications for psychology and neuroscience research.

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Introduction

Emotions have evolved to fulfill our need for fast and efficient communication, playing a pivotal role in human social interactions. Through facial expressions, people convey critical information about their thoughts and feelings, and the ability to interpret these cues is essential for effective interpersonal communication. This makes facial affect recognition a fundamental skill for understanding others' emotions and fostering positive social relationships (Spikman et al., 2013).

Like other cognitive processes, emotional processing can be divided into conscious and unconscious mechanisms (Kihlstrom et al., 2000). These two modes of processing differ qualitatively and quantitatively, engaging distinct neural pathways: unconscious processing primarily involves evolutionarily older subcortical structures (e.g., the amygdala), while conscious processing recruits cortical regions (Phillips et al., 2004; Tamietto et al., 2015). Neuroimaging studies show amygdala activation in response to masked emotional faces, even when individuals report no awareness of the stimuli (Tamietto & de Gelder, 2010). This suggests that subcortical pathways mediate rapid, automatic emotional responses, which may indirectly influence cortical activity. Tamietto and de Gelder (2010) propose that conscious and unconscious emotional processing are not entirely segregated. Instead, they involve dynamic interactions between cortical and subcortical pathways. Conscious perception engages cortical regions, which may suppress subcortical activity via inhibitory feedback—a phenomenon that could explain why subcortically driven responses (e.g., pupil dilation or facial mimicry) are paradoxically stronger during unconscious perception. For example, individuals with affective blindsight (a condition where cortically blind individuals retain unconscious emotional responsiveness) and healthy controls show heightened facial muscle activity in response to subliminal emotional stimuli compared to consciously perceived ones (Celeghin et al., 2015; Tamietto et al., 2009; Dimberg et al., 2000). Such findings highlight that emotional recognition can occur automatically, bypassing conscious awareness.

To investigate these processes, pupillometry has emerged as a powerful tool for measuring autonomic arousal linked to emotional and cognitive states. Since Hess and Polt's (1960) seminal work linking pupil dilation to emotional valence, researchers have used pupillometry to study both conscious and unconscious processing (Wang et al., 2018). Pupil size fluctuations (≈0.5 mm) reflect sympathetic activation of the locus coeruleus a brainstem nucleus regulating arousal and are sensitive to cognitive load, attention, and emotional intensity (Laeng, 2012). Critically, pupillometry captures subcortically mediated responses, making it a "window to the preconscious" (Laeng, 2012). For example, adults exhibit greater pupil dilation to masked fearful faces than neutral ones, even without conscious recognition (Laeng, 2012). Notably, these autonomic responses are diminished in populations with social deficits, such as autism, underscoring their relevance to real-world social functioning (Nuske, 2014). However, while prior work has focused on fear and happiness, the distinct pupillary responses to other basic emotions such as disgust or surprise remain unexplored, particularly in unconscious perception.

Another key aspect of emotional processing is the recognition threshold the minimum exposure time required to identify an emotion. Studies reveal systematic differences in these thresholds across emotions and populations. For instance, happiness is recognized most accurately across age groups, whereas fear recognition declines with aging (Calder et al., 2003). Subliminally, fearful faces are detected at shorter durations (10–25 ms) compared to happy or neutral faces, which require longer exposures (Tsikandilakis et al., 2021). These thresholds also vary by gender and culture, though accuracy is not strongly tied to ethnic background. Despite these advances, how recognition thresholds interact with autonomic responses like pupil dilation especially in conscious versus unconscious states remains unclear.

While prior work has often focused on fear and happiness, the distinct pupillary responses to other basic emotions such as disgust or surprise remain less explored in unconscious perception, particularly using pupillometry (Duan et al., 2010). Furthermore, the dynamics of emotions like sadness and anger across conscious states are not fully understood.

To address this gap, our study investigates how different basic emotions (happiness, sadness, anger, fear, surprise, disgust) affect pupil size during conscious and unconscious perception. Twenty-eight healthy participants completed a computerized task with masked and unmasked facial expressions while pupil size was tracked via eye-tracking. We hypothesize that: Recognition accuracy will vary across emotions, with happiness identified most reliably. Distinct pupil dilation patterns will emerge for different emotions, with fear eliciting the strongest response. Pupil dilation will be greater for unconsciously perceived stimuli due to cortical suppression of subcortical pathways during conscious processing.

By integrating pupillometry with emotion recognition thresholds, this study advances our understanding of the neural and autonomic dynamics underlying conscious and unconscious emotional processing. These findings could inform models of social functioning in clinical populations, such as autism or affective blind sight, where disrupted emotional processing contributes to social deficits.

Method

Participants

Twenty-eight healthy participants (12 females, mean age = 26.32, SD = 5.68, range 20–39) were recruited. All participants had normal or corrected-to-normal vision and completed the Spiel Berger State-Trait Anxiety Inventory (STAI) prior to the experiment to control for potential anxiety-related effects on pupil responses. Written informed consent was obtained, and participants were compensated after completing the study. The protocol was approved by the Ethics Committee of Iran University of Medical Sciences. (IR.IUMS.REC.1399.2901).

Stimuli and Apparatus

Facial stimuli were selected from the Warsaw Set of Emotional Facial Expression Pictures (Olszanowski et al., 2014), which includes seven emotional states (fear, joy, disgust, anger, surprise, sadness, neutral) and neutral expressions. To control for luminance effects on pupil size, images were standardized using Photoshop (Adobe Inc.): backgrounds were replaced with uniform gray, and stray hair/features were removed. Luminance and histograms were matched across all stimuli using the SHINE Toolbox (Willenbockel et al., 2010) in MATLAB (MathWorks Inc.). Twenty identities (10 male, 10 female) were selected as stimuli.

The experiment was programmed in PsychToolbox-3 (Brainard, 1997) and displayed on a 24-inch monitor (60 Hz refresh rate). Pupil size was recorded using an EyeLink 1000 eye tracker (SR Research Ltd.) at 500 Hz sampling rate. Participants were seated 60 cm from the monitor, with head position stabilized by a chin rest. The eye tracker was calibrated before each session using a 9-point calibration procedure in MATLAB, and validation ensured error < 0.5° of visual angle.

Facial Emotion Perception Task

The task comprised two blocks: conscious perception and unconscious perception. In the conscious perception block, emotional faces (7 emotions × 2 genders = 14 stimuli) were presented for 1000 ms. In the unconscious perception block, emotional faces were displayed for 50 ms (below conscious recognition thresholds; Morris et al., 1998) and immediately masked by a neutral face of the same identity for 950 ms using backward masking. Each block included 210 trials (14 stimuli × 15 repetitions), presented in random order. As shown in Figure 1, each trial began with a 1000-ms fixation cross to stabilize baseline pupil size, followed by emotional face presentation (1000 ms for conscious; 50 ms + 950 ms mask for unconscious). After a 500-ms delay (applied only in the conscious block to enhance perception opportunity), participants were presented with a forced-choice response screen where they selected the perceived emotion from seven options arranged circularly. Participants completed 10 practice trials before each block to familiarize themselves with the task. Both blocks lasted approximately 20 minutes, with matched repetition rates and timing.

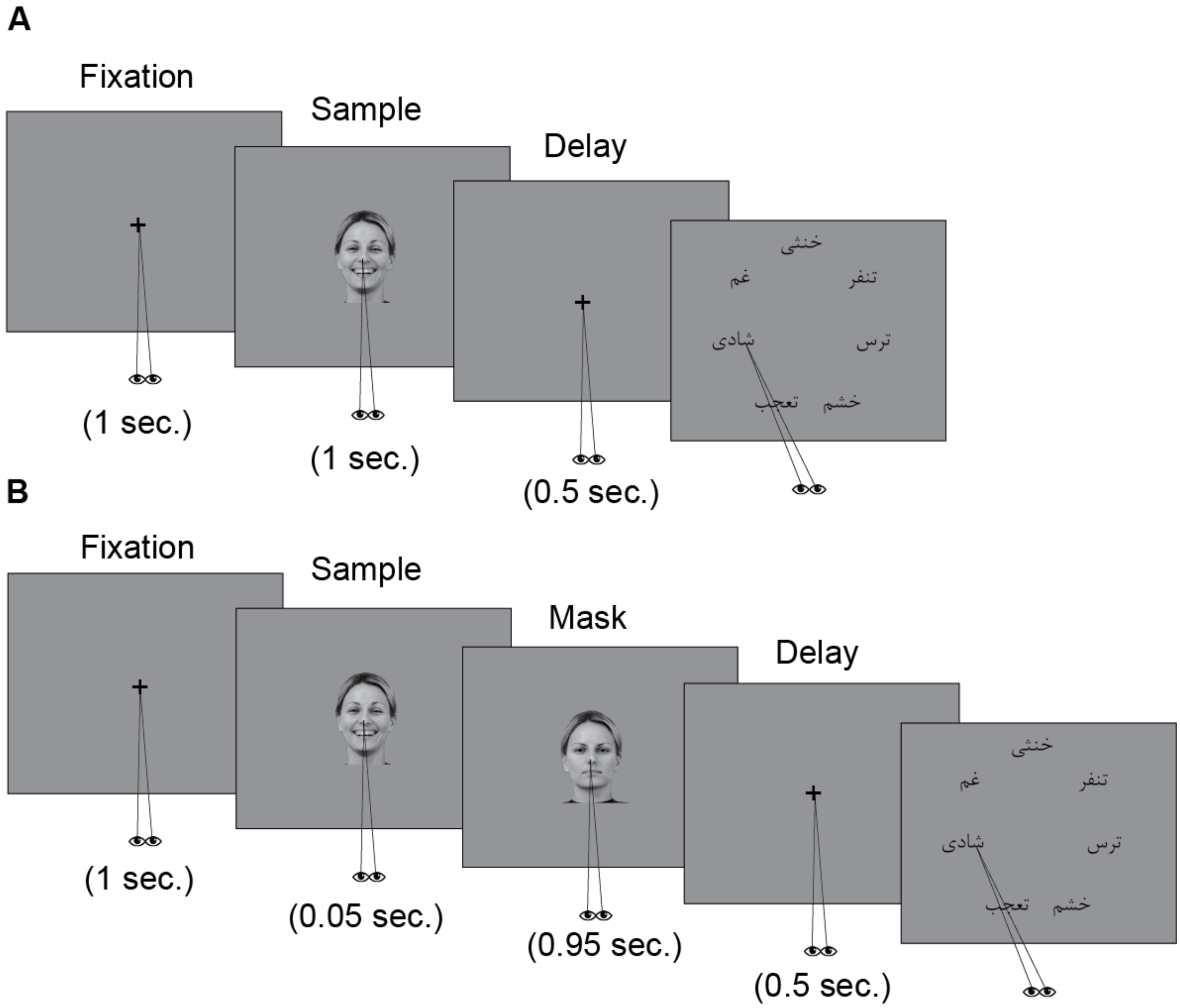

Figure 1. The schematic description of the trial sequences for behavioral tasks

(A) For conscious facial expression perception blocks, each trial began with a 1000 ms fixation cross, followed by a 1000 ms presentation of a facial expression, and then a 500 ms fixation cross. Then a response page appeared, and participants responded by saccadic eye movement to select the desired emotion name (خنثی = neutral, غم = sadness, شادی = happiness, تعجب = surprise, خشم = anger, ترس = fear, تنفر = disgust) and pushed the response key on the keyboard to finalize the response. **(B)** In unconscious facial expression perception trials, a 1000 ms fixation cross preceded a facial expression presented for only 50 ms, which was then masked by a neutral image of the same face for 950 ms, followed by a 500 ms fixation cross. Then the response page appeared until the participant made a response.

General linear modeling of pupil response

Pupil responses were analyzed using models with 6 or 8 parameters for conscious and unconscious conditions. The Pupil Response Estimation Toolbox (PRET) (Denison et al., 2020) was utilized for parameter estimation, including internal signal amplitudes and latencies, task-related response amplitudes, linear drift parameters, and baseline shifts. Each event-related signal was characterized by amplitude and latency parameters, reflecting the strength and timing of the internal signal and associated pupil response component, respectively.

Statistical analysis

Data were tested for normality using the Shapiro-Wilk test. As the data violated assumptions of normality, non-parametric tests were employed: the Wilcoxon signed-rank test for pairwise comparisons and the Kruskal-Wallis test for overall analysis. For significant Kruskal-Wallis results, post-hoc comparisons were conducted using Dunn's test with a Bonferroni correction. All analyses were conducted using MATLAB (MathWorks Inc.).

Results

The average performance of participants in both conscious and unconscious states, along with other analysis was calculated (Figure 2). Generally, participants exhibited superior performance in the conscious state ($p < 0.05$), surpassing a 70% score. The lower performance in the unconscious state was attributed to task difficulty. A Kruskal-Wallis test uncovered significant differences among various emotions in the conscious state ($p < 0.01$). Post-hoc analysis (Dunn's test) highlighted differences between anger and happiness, fear and happiness, as well as neutral and surprise ($p < 0.05$). Similar tests conducted for the unconscious state ($p < 0.01$) indicated a noteworthy disparity, particularly between happiness and all other emotions, except for neutral and surprise. Additionally, significant distinctions were observed between neutral and all emotions, and surprise with anger and sadness ($p < 0.05$).

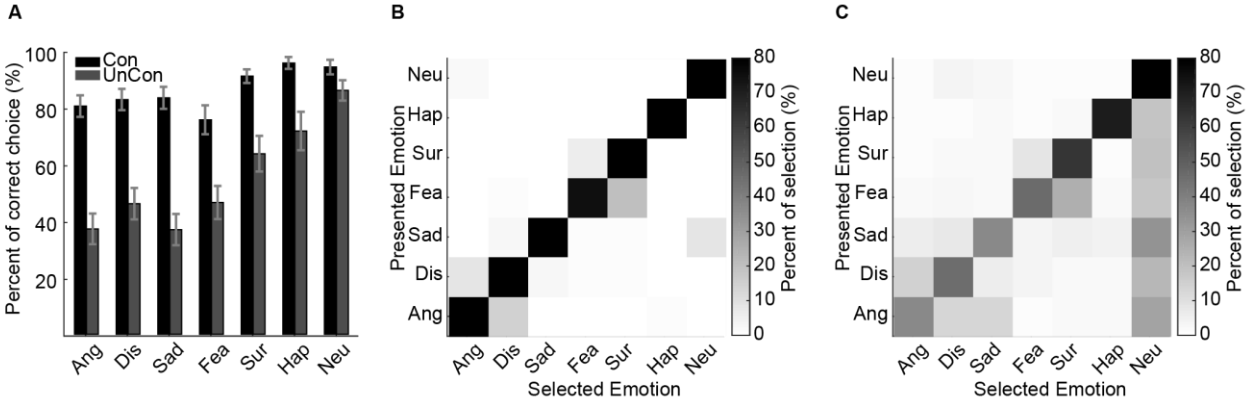

Figure 2. Behavioral performance and confusion matrix.

(A) The average performance of participants in conscious and unconscious perception for each emotion. Error bars represent the standard error of the mean. As expected, in unconscious perception, performance is lower due to the increased difficulty of the task. **(B)** Confusion matrix for the percentage of selection of emotions in the conscious state. In this figure, the vertical axis indicates the emotion displayed. In contrast, the horizontal axis represents the emotion selected by the participant, and the colors from white to black indicate the selection percentage. The main diagonal determines the correct performance, where the emotions presented and selected are the same. **(C)** Confusion matrix for the percentage of selection of different emotions in the unconscious state. As seen in the figure, there is a significant percentage of neutral responses instead of the displayed emotional expression in all emotions due to the presentation of a neutral mask.

In Panels B and C, the confusion matrices illustrate performance errors, revealing biases towards specific emotions. The conscious state matrix (Panel B) highlights challenges in distinguishing fear and surprise (19.95%) and anger and hate (14.58%). Notably, 8.59% of hate errors were misattributed to anger, while 5.87% of surprise errors were associated with fear. Although participants correctly identified sadness in 82.61% of cases, 8.54% of remaining trials were selected neutral. Happiness trials yielded the highest accuracy (94.79%) without discernible biases. Overall, participants exhibited performance biases despite pre-experiment training.

The confusion matrix delineating the unconscious state is presented in Panel C. Similar patterns to those observed in the conscious state manifest, notably biases between fear and surprise, and anger and hate. Given the neutrality of the mask, participants exhibited discernible errors by selecting the neutral state, instead of the correct emotion. Comparisons between the conscious and unconscious states reveal subtle distinctions. For instance, misattribution between sadness and anger, as well as sadness and hate, were notably elevated (5.97 and 7.75, respectively). Correct selection of happiness occurred significantly less frequently than the conscious state

(71.03). Similarly, fear was chosen correctly at a diminished rate (46.02), with 24.72% of the remaining inaccuracies pertaining to surprise.

Pupillometry Results

Pupil size was measured in both conscious and unconscious states, revealing a conspicuous pattern of suppression in the conscious state and enhancement in the unconscious state. Notably, there is an initial increase in pupil size within the first 500 ms for both states. In conscious trials, the pupil size experiences suppression, attributed to cortical networks inhibiting further changes through inhibitory back-projection. Conversely, this trend is absent in the unconscious state, where pupil size demonstrates an escalating slope. Furthermore, distinctions between rise time and pupil size across different states are observed which are discussed in subsequent figures.

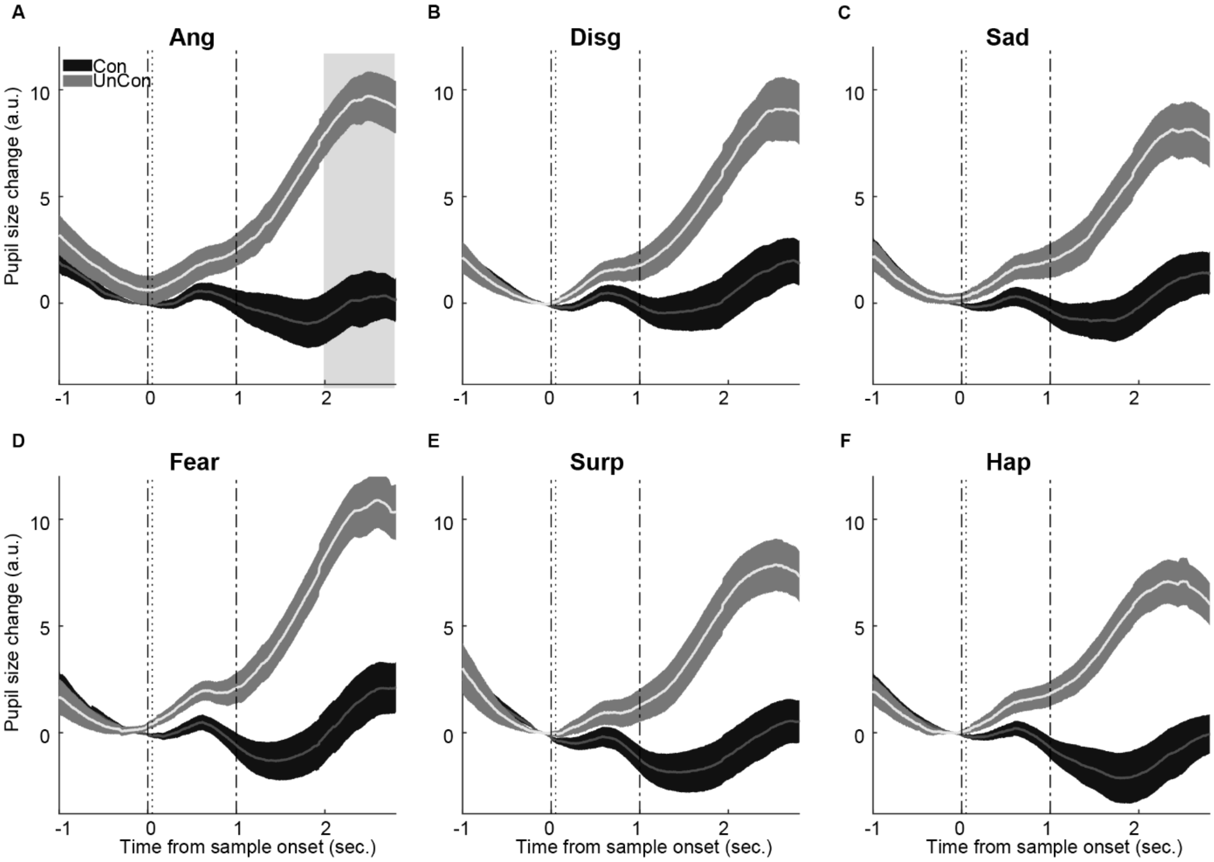

Figure 3. Modulation of pupil size changes for different emotions during conscious and unconscious perception The lighter shades represent pupil size changes during unconscious detection tasks, while the darker shades represent those during conscious detection tasks. As shown in the figure, all emotions elicit more significant changes in pupil size during unconscious perception than conscious perception. Additionally, there appears to be a difference in pupil dilation for different emotions, and the rise time for each emotion varies. The shaded area in the first plot represents the time interval during which the most significant changes in pupil size occur (between 2000 and 2800 ms after stimulus onset), and it has been used for further analysis.

Panel A displays the peak pupil size for correct trials in both conscious and unconscious states. No discernible change was observed in neutral trials. A Wilcoxon signed-rank test revealed significant differences for two states of consciousness for each emotion ($p < 0.00$), except for neutral ($p = 0.07$). ANOVA analysis did not indicate significant differences between emotions in the conscious state. However, there was a significant disparity in peak pupil size during the unconscious state. Post-hoc analysis identified this difference specifically between neutral and fear conditions.

In Figure 4 (B and C), the confusion matrix for peak pupil size in both states of consciousness is presented. Unlike Panel A, Panels B and C encompass all trials, not solely the correct ones. The vertical axis denotes the presented emotion, while the horizontal axis represents the selected emotions. The main diameter of the confusion matrices signifies the correct trials. As mentioned, the matrices include instances where the wrong emotion was selected, but trials with fewer than 5 errors were disregarded due to potential external factors. Noteworthy is the absence of significant changes in the conscious state (Panel B), except for instances where participants selected fear. Conversely, the unconscious state exhibits significant pupil dilation, even when emotions are incorrectly selected. Notably, when fear and surprise are chosen correctly or incorrectly, there is a discernible increase in pupil size. The accompanying histogram illustrates presented and selected emotions. In the conscious state, major changes are absent. However, the confusion matrix for the unconscious state reveals that pupil dilation are determined by the selected (perceived) emotions rather than the presented ones. The histogram indicates that the highest recorded pupil size change occurs when the perceived emotion is fear.

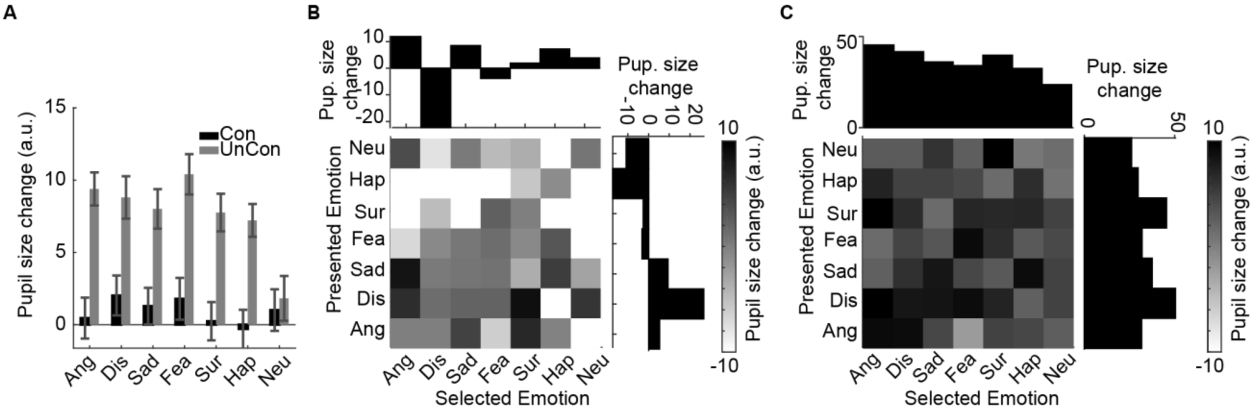

Figure 4. Difference between pupil size changes in different emotions
(A) This panel demonstrates the variations in pupil size for trials where the correct answer was selected for both conscious and unconscious tasks. There is a minimal observable change in pupil size for neutral stimuli in both conscious and unconscious states and for emotional stimuli in the conscious state. Error bars represent the standard error of the mean. **(B)** Confusion matrix of pupil size change for different emotions in the conscious state. The upper barplots demonstrate changes in pupil size when the target emotion is selected, irrespective of the particular emotion displayed. The barplots on the right illustrate variations in pupil size when a specific emotion is displayed, regardless of which emotion is selected. **(C)** Confusion matrix of pupil size change for different emotions in the unconscious state.

In the conscious state, when the presented stimulus is positive and the subject mistakenly selects a negative emotion, there is a decrease in pupil size. Also, there are different pupil size changes with the emotion of disgust. In the unconscious state, there is a more significant increase in pupil size overall. The unconscious state exhibits significant pupil size changes, even when emotions are incorrectly selected. Notably, when fear and surprise are chosen correctly or incorrectly, there is a discernible increase in pupil size, with more pronounced changes during negative emotions. Disgust evokes a greater increase when it is the presented emotion. Using peak response alone may not decode the types of emotion and their processing speed accurately. We utilized modeling tools to investigate these parameters more precisely.

General linear modeling of pupil response

Using the modeling, we investigated the different components of the task in the production of pupil response. Based on the work of Hoeks and Levelt (1993), pupil response models typically assume two points (Hoeks & Levelt, 1993). First, the models assume a stereotyped pupil response function (PuRF) like a gamma function, which describes the time series of pupil dilation in response to a brief event. Second, the models assume that pupil responses to different trial events sum linearly to generate the pupil size time series; that is, they are general linear models (GLMs) (Figure 5). Using this model, we aimed to separate different components and assess their contributions to pupil response. Generally, three important components should be evaluated: task-related response, amplitude, and latency of emotional stimuli presentation.

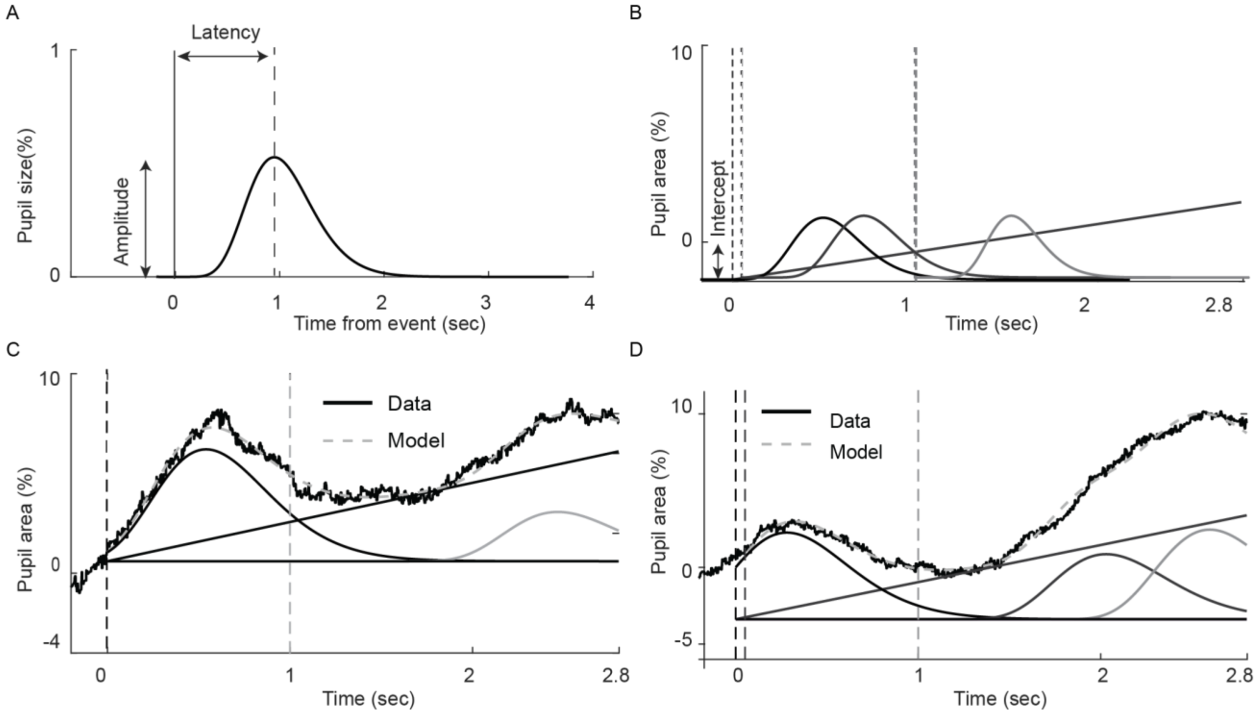

Figure 5. The modeling of the pupil time series.

(A) a Pupil response function, which describes the pupillary response to an event. The canonical function, a gamma function with n = 10.1 and tmax = 930 ms (vertical dashed line), is shown. **(B)** Trial events hypothesized to drive pupil dilation. Each trial event (visual stimuli) is modeled as a delta function (vertical dashed lines) with some amplitude and some latency with respect to the event. For conscious we have two events at 0 sec, onset of stimulus and 1 sec, offset of stimulus and for unconscious we have one event more presentation of mask at 5o ms after stimulus onset. As line (slop and y- intercept), task-related signal could also be modeled. Shown here is in a solid line. **(C, D)** The pupil time series across (black line) is modeled in two steps. First, each internal signal time series is convolved with the pupil response function to form component pupil responses. Second, the component pupil responses are summed to calculate the model prediction (gray dashed line). Parameters of the model, such as the amplitudes and latencies of the internal event signals, are fit using an optimization procedure. (C) is for sample conscious and (D) is for unconscious trials.

We assumed a linear function as the task-related component for each trial and one baseline shift parameter. These parameters differed for conscious and unconscious states (Figure 6A-B). For the conscious state, angry and surprise have negative slopes, while fear has a positive slope. For the unconscious state, the slope parameter is positive except for neutral, in which there was no emotion. There were no differences in task-related slopes among unconscious emotions. The baseline value is also negative for unconscious emotions and disgust emotion in the conscious state.

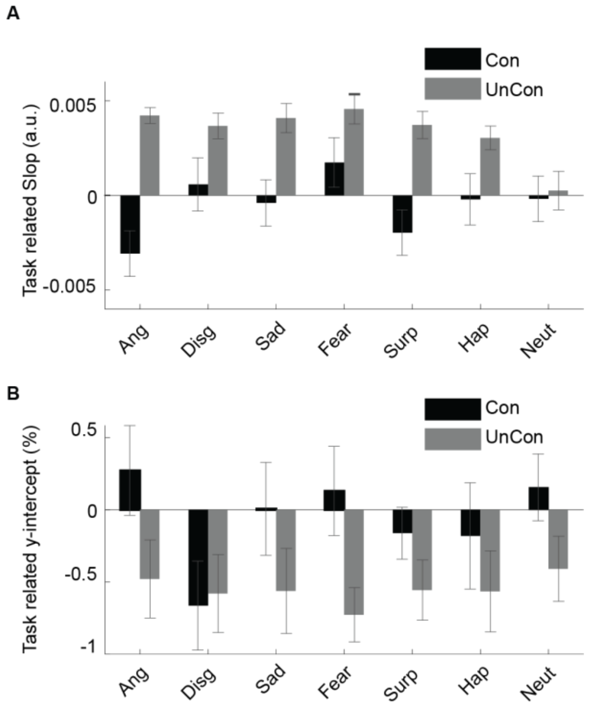

Figure 6. Task related Model parameters over subjects. Tasl related parameters, upper plot slope of line and lower plot y- intercept.

Each event had a response function with an amplitude parameter and a latency parameter associated with it. The amplitude parameter was the value of the nonzero point of the delta function and indicated the magnitude of the internal signal, determining the magnitude of the component pupil response associated with it (Figure 7). The first event for each state is the emotion-related event (amp1 Con and amp1 UuCon). For conscious states, the emotion-related amplitude did not differ between emotions. Similarly, in unconscious states, the emotional response did not differ between emotions.

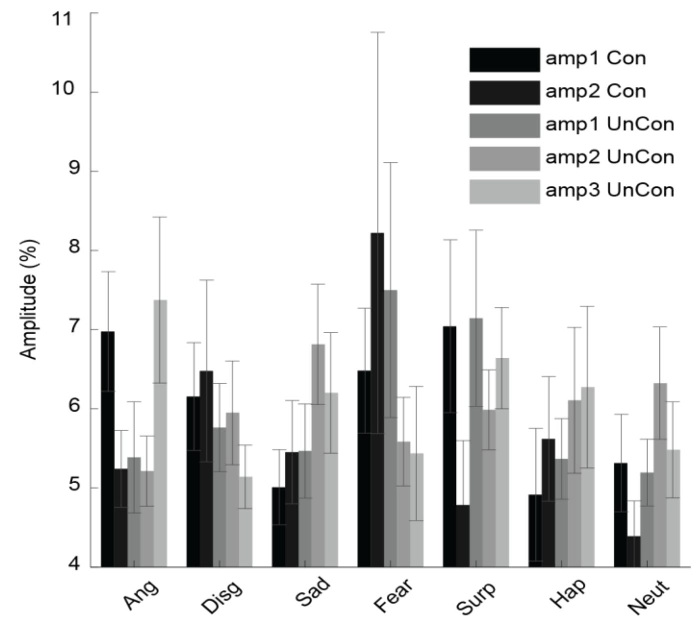

Figure 6. The effect of different events from Model parameters over subjects. Amplitude for different events “amp1 Con” onset stimulus, “amp2 Con” offset stimulus, “amp1 UnCon” onset stimulus, “amp2 UnCon” onset mask and “amp3 UnCon” offset stimulus.

The latency parameter was the time (in ms) of the nonzero value, relative to the time of its corresponding event. The pupil latency reflected the speed of the emotional response (Figure8). In conscious states, the emotion-related latency did not differ between emotions. Happy and angry were the fastest, while surprise and neutral were the slowest in conscious states. In unconscious states, sad, fear, surprise, and happy were the slowest responses, while disgust was the fastest.

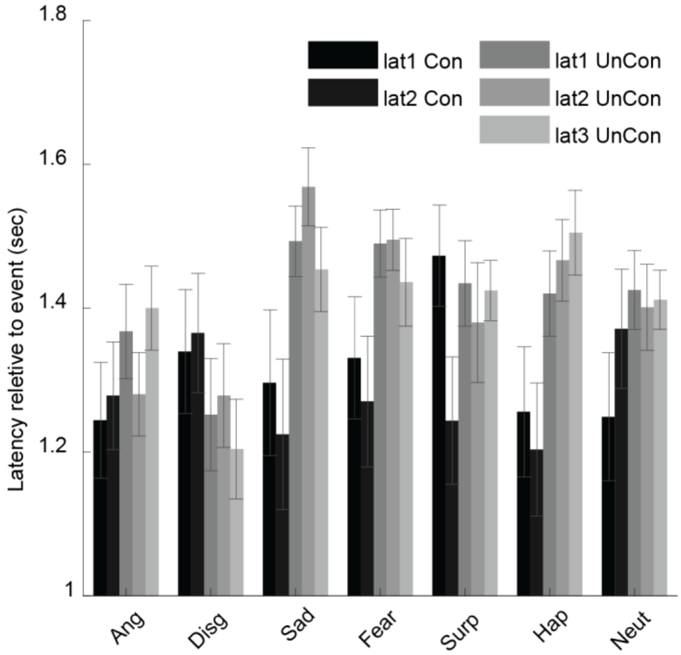

Figure 8. The speed of different events from Model parameters over subjects. latency for different events lat1 Con" onset stimulus, "lat2 Con" offset stimulus, "lat1 UnCon" onset stimulus, "lat2 UnCon" onset mask and "lat3 UnCon" offset stimulus.

Correlation analysis (Spearman's rank) between peak pupil size and demographic factors (age, sex, education level, STAI score) showed no significant correlations (all $p > 0.05$), indicating that pupillary responses were not confounded by these variables.

Discussion and Conclusion

This study aimed to investigate the behavioral and pupillometric correlates of conscious and unconscious processing of six basic emotions. We hypothesized that (1) recognition accuracy would vary across emotions, with happiness being the most identifiable; (2) distinct pupil dilation patterns would emerge for different emotions, with fear eliciting the strongest response; and (3) pupil dilation would be greater for unconsciously perceived stimuli due to reduced cortical inhibition.

Our results confirm these hypotheses. We found that recognition accuracy was highest for happiness in both states, supporting its role as a primordial and easily processed emotion. Furthermore, pupillometry revealed a clear dissociation between states: unconscious perception was characterized by enhanced pupil dilation, while conscious perception showed relative suppression. This pattern is consistent with the proposed model where conscious, cortical processing inhibits subcortically-driven autonomic responses [**Cite e.g., Tamietto & de Gelder, 2010**]. Notably, fear elicited the most robust pupillary response, especially when perceived unconsciously, underscoring the salience of threat-related stimuli even in the absence of awareness.

It is important to note that we found no significant correlations between pupillary responses and demographic factors such as age, gender, education level, or trait anxiety. This suggests that the core effects of emotional processing on autonomic arousal, as measured by pupillometry, are robust across these individual differences in our healthy sample.

The findings reveal a consistent increase in pupil size during emotional perception compared to neutral stimuli, irrespective of valence, supporting the hypothesis that emotional processing imposes cognitive load (Partala et al., 2003). Critically, these pupillary changes were independent of low-level stimulus properties (e.g., luminance), reinforcing their link to emotional arousal. In unconscious trials, heightened pupil dilation during the response period aligns with evidence that facial expressions influence autonomic responses even without conscious awareness (Eastwood & Smilek, 2005; Tamietto et al., 2009). Notably, unconscious stimuli elicited larger pupil changes than conscious ones, potentially reflecting heightened subcortical arousal (Tamietto & de Gelder, 2010) .

The observed unconscious pupil dilation may not solely stem from cortical inhibition. Competing explanations must be considered, such as cognitive load, as increased mental effort during unconscious processing could drive pupil dilation. Prior work demonstrates that cognitive demand amplifies pupillary responses (Kiefer et al., 2016; Gavas et al., 2017), suggesting that the effort to process masked stimuli might contribute to the observed effects. Another possibility is covert attention, as unconscious shifts in focus toward emotional stimuli might mediate dilation (Mathot et al., 2013). Disentangling these mechanisms requires future studies that isolate attention and cognitive load from inhibitory cortical-subcortical interactions .

The transient pupil size reduction approximately one second after unconscious stimulus onset (Figure 3) may reflect inhibitory feedback from cortical to subcortical regions (Tamietto & de Gelder, 2010). However, the subsequent rebound in dilation could arise from fading inhibition and reactivation of excitatory subcortical pathways. This interplay underscores the dynamic neural coordination underlying unconscious emotional processing. Caution is warranted when extrapolating these results, as age-related differences in emotion recognition (Calder et al., 2003) and individualized perceptual thresholds (Tsikandilakis et al., 2021) suggest our findings may not generalize across demographics. For instance, younger adults typically outperform older adults in facial recognition tasks, except for disgust (Calder et al., 2003). Furthermore, fixed experimental thresholds risk conflating subliminal perception with methodological bias, as Tsikandilakis et al. (2021) demonstrated using Bayesian methods. Future work should tailor thresholds to participants and emotions to mitigate such biases .

The GLM approach revealed temporal disparities in pupil responses: conscious trials showed emotion-specific latencies (e.g., happiness: 320–335 ms), while unconscious responses were slower overall (peaking at 510–520 ms for fear/surprise). These patterns highlight distinct temporal dynamics between conscious and unconscious processing, though amplitude consistency suggests comparable arousal magnitudes .

In conclusion, this study elucidates how conscious and unconscious emotional perception differentially engage pupillary and neural mechanisms. While conscious recognition prioritizes cortical accuracy, unconscious processing amplifies subcortical arousal, reflected in heightened pupil dilation. Fear and happiness emerged as pivotal emotions, with fear triggering robust unconscious responses even when misclassified. These findings underscore the dual pathways of emotional processing and emphasize the need for demographic-sensitive methodologies in future research. By addressing unresolved questions such as the roles of cognitive load and attention this work advances frameworks for studying social perception in both typical and clinical populations.

Declarations

Author Contributions

All authors contributed actively to the conception, design, and execution of the research.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Ethical considerations

This study was conducted in accordance with the ethical standards of the Declaration of Helsinki. The research protocol was reviewed and approved by the Ethics Committee of Iran University of Medical Sciences (Approval Code: IR.IUMS.REC.1399.2901). All participants were informed about the general aims and procedures of the study and provided written informed consent prior to participation. Confidentiality and anonymity of the participants' data were fully maintained throughout the research process.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this research.

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The Effect of Self-Regulatory Education Based on the SRSD Model on Executive Function in Children with Learning Disabilities in Math and Writing Problems

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Self-regulatory education program, SRSD-based self-regulatory education, Executive function, Children with learning disabilities.

ABSTRACT

Backgrounds: Children with learning disabilities are children who are weak in one or more basic psychological processes. Executive function is one of the important cognitive processes that play an important role in academic performance. Objectives: In this regard, the present study aimed to prepare a self-regulatory education program based on SRSD and investigate its effectiveness on executive function, Cognitive-Learning content areas and academic achievement of children with learning disabilities. Methods: The present study is a semi-experimental study with pre-test and post-test .sample of 30 children with learning disabilities in Gorgan, including 15 in the control group, and 15 in the experimental group was selected. The instruments used in this study included LEAF scale (2016) and WISC-IV (2003), which was implemented and scored in two stages, before and after the self-regulation training program based on SRSD. Data analysis was performed using multivariate variance analysis using SPSS software version 26. The $P<0.05$ were considered for data analysis and as significant levels respectively. Results: The results of multivariate variance analysis showed self-regulatory education has been able to reduce weaknesses in Cognitive-Learning content areas (Comprehension and Conceptual Learning) ($p<0.001$), executive function components (Factual Memory, Attention, Visual-Spatial Organization, Sustained Sequential Processing, Working Memory, Novel Problem Solving)) ($p<0.001$), academic achievement (Mathematics Skills, Basic Reading Skills, Written Expression Skills) ($p<0.001$) and promote the components in these children. Conclusion: The findings of this study show that educational program can be effective in improving cognitive learning content, executive function components, and academic achievement in children with learning disabilities.

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Introduction

Learning disability includes problems with poor reading, poor writing, and math disorders, and refers to a disorder in one or more basic psychological processes related to understanding or using spoken or written language. The disorder may manifest as problems with the ability to listen, think, speak, read, write, or do math calculations. In the diagnostic manual of mental disorders, learning disabilities are classified as dyslexia, dyslexia, and math disorder. (Association AP, 2015)

Children with learning disabilities have problems in their other functions due to malfunctioning of the nervous system, differences in psychological processing, and defects in information processing. Mathematical disorder causes problems in solving problems and calculations using inappropriate strategies appropriate to the problem, and problems in learning and remembering mathematical concepts (Arslani et al., 2019)

Writing disorder is a category of learning disorder that causes problems in the cognitive processing and writing skills of a person. A person with a written learning disorder has problems in auditory processing content processing and rapid automatic naming. (Sangani, war, Priya, ramek, 2019) One of the problems of children is problems in executive functions. Executive functions are complex cognitive processes that create purposeful behavior and are usually associated with disorders and are one of the influential areas of executive function weakness (Hosseinidashtbayaz et al., 2020).

Dowson & Guare (2004) consider executive functions to include 5 skills, including planning skills that create a plan to achieve a goal or complete a task, The power to organize includes making decisions and recognizing important and unimportant matters, designing and maintenance of information and time management, working memory, which includes storing information in memory while working, and self-monitoring skills (Dowson, McInerney, 2004)

This function includes all the cognitive skills that help a person to pay attention focus and perform activities, therefore this function is effective in the academic progress of people (McClelland, Cameron, 2019) Children with learning disabilities are a group of children whose executive functions are in trouble, and weakness in this function impairs their reading, writing, and math skills (Babaei et al., 2012). Executive function is an effective factor in math learning and one of the causes of children's math problems is their weak executive function (Arshad, kasheffi, 2021). Also, executive function affects writing, and one of the factors affecting writing disorder is weakness in executive functions (Hadi et al., 2017)

Operationally, executive function is the score that children get on the scale of executive function, attention, and learning function (Castellanos et al., 2016)One of the factors affecting children's executive functioning is the use of self-regulation training (Mansour, 2013)

Self-regulation training makes children learn self-regulation strategies. The use of these strategies causes the child to have self-control over the learning process and start planning, organizing, and monitoring, if a strategy is not effective, change it, and in this way, it can affect the executive function (Ebrahimi, 2019) Self-regulation training is a factor that helps people to use self-control, self-assessment, planning, and monitoring skills in different stages of learning and become self-regulation learners (Neemchahi et al., 2018)

In the last decade, the approach that has evolved in the field of cognitive and metacognitive skills is the self-regulation approach. Self-regulated learning training causes people to increase their learning, understanding, and concentration by using appropriate cognitive and metacognitive strategies, and as a result of this, their anxiety decreases, and their emotional self-efficacy increases. Also, by learning this skill, learners can pursue assignments and have a good performance in solving problems. (Ghasemi et al., 2015)

Self-regulated strategy development (SRSD) is an evidence-based method for children with learning disabilities (Baker et al., 2015) Cognitive strategy training is specific to academic skills that are focused on training (Rogers, Hodge, Counts, 2020). SRSD is an educational framework that is effective for students with learning disabilities or students who are prone to failure or difficulty in writing, reading skills, and mathematics (Hagaman et al., 2016)

SRSD includes training methods that solve executive function problems and specifically, SRSD affects the components of decision-making and planning, implementation and coordination of mental and emotional resources, attention control, and flexible adaptation (Harris et al., 2018)

The self-regulation training program is a program that helps people first learn about various self-regulation strategies, then internalize those strategies and use them independently by discussing and practicing various issues and activities. The SRSD framework includes explicit instruction, cognitive strategy instruction, self-regulation instruction, and recall to help children remember the steps of a process.

In the current research, the SRSD model is taught to children in the form of 6 stages, in the order of development of background knowledge, discussion, and discussion, modeling of the model, retention of strategies, support for it, and independent performance of the child.

Research results show that self-regulation training has an effect on children's executive function, and executive function plays an important role in children's learning disorders, and strengthening it has a positive effect on learning disorders. However, so far, there has been no study investigating the effectiveness of self-regulation training based on the SRSD model and investigate its effectiveness on learning, executive function, and academic skills of children with learning disabilities. In line with this main goal, this study sought to answer the following questions:

1. Is self-regulation training based on the SRSD model effective on the cognitive subscale of learning in children with learning disabilities?
2. Is self-regulation training based on the SRSD model effective on the subscale of cognitive executive function in children with learning disabilities?
3. Is self-regulation training based on the SRSD model effective on the subscale of academic skills in children with learning disabilities?

Method

Research Design

The present study was semi-experimental applied research of pre-test and post-test type with a control group consisting of 30 children with learning disabilities in Gorgan city. The sampling method in this research was a non-random sampling of the available type. The tools used in this research include the learning scale, executive function, and attention of Castellano, Kronberger, and Pisoni (2013) the fourth version of the Wechsler intelligence scale (2003) for children.

After interviewing and evaluating children using the Wechsler scale determining the normality of their intelligence (IQ score of at least 70 ± 5)and diagnosing learning disorders in them through the learning scale, executive function, and attention, children with weakness in executive function were identified .The design of the study was carried out according to self-regulation education, including the stages of developing background knowledge, discussion, and dialogue, modeling it, maintaining strategies, supporting the child to follow it, and performing the child's independent performance.

This study has an ethics code to ID (IR.UT.PSYEDU.REC.1401.072) from the Faculty of Psychology and Educational Sciences, University of Tehran. Among the ethical principles respected, the confidentiality of information, voluntary withdrawal from the research, and no harm to the participants.

Sample of the Study

The population of this study was all children with specific learning disorders who were referred to Hekmat Learning Disorders Center in the academic year of 1401-1400 in Gorgan city. 30 male children including 15 in the control group, 15 in the experimental group in the age range of 8 to 12 years in the manner available sampling was selected (Table 1).

The criteria for entering the research include consent of parents and children to participate in the research based on written consent, male students between the ages of 8 and 12, children with specific learning disabilities,(Dysgraphia , and Dyscalculia), and children who have weaknesses in our executive functions (according to the learning, executive function, and attention scale questionnaire, the range 5-15)The criteria for the withdrawal of participants from the research included: non-cooperation and unwillingness of the participants to continue the sessions, absence of more than two sessions in the training sessions, and history of receiving psychological interventions related to the problem.

Table 1. Characteristics of the research sample

Group	Disorder	Frequency
Treatment	Math And Writing Disorder	15
Control	Math Disorder	2
	Math And Writing Disorder	13

Data Collection Instruments and Methods

The scale of learning, executive function, and attention:

In this study, the scale of learning, executive function, and attention was used to measure executive function and learning skills in children and adolescents aged 7 to 17 years, which was designed by Castellano, Kronberger, and Pisoni (2013) This scale includes two parts of cognitive-learning content; which includes the skill of learning, memory, and reasoning, which are close and related to executive function but are not part of the basic structure for executive function. Two subscales of cognitive content learning are the executive function scale, attention function, and learning. 1 item was considered for each factor and as a result, 11 items were created. Items were rated on a 0-3 Likert scale; by summing the 5 items related to each 11 subscales, a total score of 55 is obtained, so higher scores indicate more problems (Faries, et al., 2001)

A rating of 2 (often) is used for behaviors that cause problems, while option 1 (sometimes) reflects behaviors that may occur more than average but do not cause a major problem; Therefore, the average scores related to choosing option 2 for the five items of each subscale show that the behaviors related to that subscale occur more than average and happen almost every day and cause problems. Also, in the scale of executive functioning, attention, and learning, 3 criteria were considered to interpret problems .Cronbach's alpha coefficients for executive function scale, attention, and learning function and its subscales, respectively, 0.88, 0.91, 0.85, 0.71, 0.79, 0.80, 0.70, 0.82, 0.93, 0.89, 0.77 were obtained, which indicates high internal consistency. to check the reliability of the Persian version of the executive functioning scale, performance, and stability of attention and learning, two methods of internal consistency were used. In examining the internal consistency of the scale, Cronbach's alpha was calculated and its validity and reliability were confirmed in research (farzadi et al., 2020) Test-retest reliability results for subscales are 0.41, 0.71, 0.82, 0.86, 0.89, 0.72, 0.85, 0.63, 0.82, 0.88 respectively. 0.79 was obtained.

The differential validity and discrimination power of the scale were used by comparing the subscales in terms of two age groups using the independent two-group Test-T method. To check the criterion validity, the scale of executive function, attention, and learning performance with the rating of executive function behavior, as well as neuropsychological tools of executive functions (Simon's color word test and homework)(nejati et al.,2021) and Woodcock Johnson's academic achievement test was used. The results of the research show that the cognitive learning subscale of the executive function scale, attention and learning performance, are correlated with the attention problems subscale of the shortened scale of hyperactive behavior and attention problems and disobedience symptoms and the executive function behavior rating subscales.

The fourth version of the Wechsler intelligence scale for children:

The fourth edition of Wechsler's Children (2003) can measure the intelligence of children in the age range of 6 to 16 years and 11 months. This tool has 15 sub-tests which are divided into two groups of main and substitute sub-tests. The mean of each subtest is 10 and its standard deviation is 3. Also, the fourth version of the Wechsler IQ scale can measure intelligence, verbal comprehension, perceptual reasoning, active memory and processing speed, verbal comprehension, executive reasoning, verbal reasoning, active memory, and processing speed with a mean of 100 and a standard deviation of 1 (Farid et al.,2015) From the total of ten sub-tests of these four scales, the IQ of the whole test can be calculated. This test was translated, adapted, and standardized in 2016 by Abedi, Sadeghi, and Rabiei with the financial support of Chaharmahal and Bakhtiari Education Organization. The reliability coefficients of the subtests are reported by Cronbach's alpha (between 0.65 and 0.94) and also by the halving method between 0.76 and 0.91. The validity of the test has been reported at a favorable level through simultaneous implementation with Wechsler, Shahim, and Riven. All reliability coefficients are more than 0.7, which indicates the reliability of the test (Tayyaba, Mohammad, 2013)

Experimental Application Process

The research design was considered by studying the theoretical and experimental backgrounds in this field. Programs already designed for self-regulation training were also reviewed to consider their strengths. The lesson plan for each session, educational tools, pamphlets, and children's homework were set. First, to enter the Hikmat Learning Disorders Center in Gorgan City, an introduction letter from the university was delivered to the center's management, and with the cooperation of the Gorgan Learning Disorders Centers and with their consent, access to the samples was possible.

First, to enter the Hikmat Learning Disorders Center in Gorgan City, an introduction letter from the university was delivered to the center's management, and with the cooperation of the Gorgan Learning Disorders Centers and with their consent, access to the samples was possible .
After selecting the samples using the available sampling method and selecting the children with learning disabilities by performing the Wechsler children's test and diagnostic interview and diagnosis of learning disabilities, they were divided into two groups of 15 people and were placed in the control and experimental groups.

Before the start of the training, the executive function and attention questionnaire of Castellano et al(١٠)was implemented and scored, and after the implementation of the self-regulation training program based on SRSD, the executive function and attention questionnaire of Castellano et al. was implemented and scored again. The intervention was in the form of an educational program and the formation of a class for the participants. The development of the intervention program was also under the supervision of experts.

The validity of the program was reviewed and approved by experts and corrections were made. This research is based on the previous research of Sohrabi et al., (2014); Seydi et al. (2021) ; Wanzek et al.(2021) ; Stevens et al.(2021) ; it was done in groups and groups of 2 or 3 people, and the intervention was done for 12 sessions and in 6 weeks of 2 sessions.

Reliability Analysis of the Scales

To check the validity of the content, a copy of the self-regulation training program along with a checklist was prepared with the aim of checking the theoretical suitability and behavioral examples and was given to 5 experts in this field to rate the suitability of each intervention session on a Likert scale (from 1, the lowest suitability to 10, which is the most suitable for the program). The formal and content validity of the presented model was calculated using the content validity index (CVI) (Table 2).

Table 2. Content Validity Index Based on Judges' Opinions

Judges	Meetings												Mean
	1	2	3	4	5	6	7	8	9	10	11	12	
1	8	9	10	9	9	7	8	9	10	9	8	8	8.66
2	5	6	7	7	5	3	4	5	6	6	7	6	5.58
3	9	9	8	9	9	9	9	9	9	8	9	9	8.83
4	6	6	7	8	7	8	9	8	9	9	10	9	8
5	6	7	7	7	7	7	6	7	7	8	7	6	6.83
Mean	6.8	7.4	7.8	8	7.4	6.8	7.2	7.6	8.2	8	8.2	7.6	

Data Analysis

After collecting pre-test and post-test data, the collected data were analyzed with statistical tests. In this research, descriptive statistics such as frequency, mean, and standard deviation, and inferential statistics including multivariate covariance analysis were used to control the pre-test variable, and the data analysis software was SPSS version 24.

Results

Table 3 shows the frequency of people in two pre-test and post-test groups who were placed in two control and experimental groups. In Table 4, information about the number of participants in the two control and experimental groups and information about the age groups present in the sample is given. (Table 3, 4)

Table 3. The Frequency of People in the Control and Treatment Groups in Two Stages of Measurement

Group	Pre-Test	Post-Test	Total
Treatment	15	15	30
Control	15	15	30
Total	30	30	

Table 4. Frequency related to class age groups of sample people

Class age group	Treatment		Control	
	Frequency	Percent	Frequency	Percent
Third grade	2	0.13	1	0.06
fourth grade	6	0.4	1	0.06
Fifth grade	5	0.33	7	0.46
6th grade	2	0.13	6	0.4

In Table 5, the descriptive statistics related to the mean and standard deviation of the scores of the executive function components for the individuals of the control and experimental groups are given separately in two stages of measurement. In the control group, the average scores in the pre-test and post-test stages did not change much, but in the experimental group, we saw a significant decrease in the post-test scores compared to the pre-test, and it shows that the degree of weakness in the components of executive function has decreased in the post-test scores. Also, in the follow-up phase, the scores of the control group increased slightly, but in the experimental group, the scores decreased, indicating a decrease in the degree of weakness in the executive function components in the follow-up phase. (Table 5)

Table 5. The mean and standard deviation of the scores of executive function components in the two stages of the test, separately for the treatment and control group

Group	Variable	Pre-test Mean	Pre-test SD	Follow-up Mean	Follow-up SD	Post-test Mean	Post-test SD
Control	Understanding learning	7.33	1.45	7.25	1.48	8.48	1.34
	Real memory	7.92	1.67	6.90	1.42	7.36	1.70
	Attention	8.27	1.81	7.17	1.24	7.88	1.52
	Processing speed	7.13	1.27	7.47	1.36	7.96	1.75
	Visual organization	7.63	2.20	6.80	1.57	7.86	1.56
	Stable sequential processing	8.05	1.98	6.93	1.33	6.98	1.34
	Working memory	8.65	1.45	7.47	1.06	8.77	1.00
	New problem solving	8.10	1.83	7.13	1.13	8.13	1.46
	Math skills	8.46	1.48	7.92	1.18	8.24	1.13
	Basic reading skills	8.76	1.35	7.20	0.86	7.89	0.89
	Written expression skills	8.10	1.99	7.07	1.44	7.96	1.49
Treatment	Understanding learning	9.13	3.48	5.34	3.13	4.32	3.12
	Real memory	9.18	3.74	5.87	4.05	4.09	3.08
	Attention	9.81	2.91	6.64	3.39	6.04	3.13
	Processing speed	6.59	3.34	7.00	4.14	6.56	3.15
	Visual organization	9.36	3.15	5.80	3.28	5.00	3.27
	Stable sequential processing	9.20	3.73	5.67	4.55	5.45	3.51
	Working memory	10.41	2.98	6.40	3.79	6.02	3.84
	New problem solving	9.76	3.25	5.47	3.56	4.67	3.35
	Math skills	10.36	2.82	6.24	3.21	5.23	3.05
	Basic reading skills	9.77	3.99	5.67	4.50	4.45	3.80
	Written expression skills	9.27	3.98	4.07	3.58	3.06	3.05

In this section, the assumptions are tested primarily for the analysis of the data. Then, answers were given to the research problems in order.

1. Self-regulation training program based on SRSD affects the cognitive subscale of learning.

To investigate the effectiveness of the self-regulation program based on SRSD on the cognitive subscale of learning, the multivariate analysis of covariance (MANCOVA) test was used. Before performing this test, it is necessary to check some statistical assumptions. One of the assumptions of the multivariate covariance analysis test is the homogeneity of the covariance matrix, and the Box's M test was used to check the establishment of this assumption. The results of this test are shown in (Table 6)

Table 6. The result of homogeneity of the covariance matrix for cognitive learning subscale (Box's M)

Box's M	F	df1	df2	p-value
131.04	1.44	55	2531.77	0.018

As can be seen in Table 6, the significance level of the box test is equal to 0.018. Since this value isnt greater than the significance level (0.05) needed to reject the null hypothesis, our assumption of the homogeneity of the covariance matrix isnt confirmed. This is one of the limitations of the research.Another assumption of the multivariate covariance analysis test is to check the normality of the pre-test and post-test score distribution, and the Kolmogorov-Smirnov test was used to check the establishment of this assumption. The results of this test are shown in (Table 7).

Table 7. Kolmogorov-Smirnov test results to check the normality of the distribution of scores

Variable	Pre-Test		Post-Test	
	Kolmogorov-Smirnov	p-value	Kolmogorov-Smirnov	p-value
Understanding learning	0.138	0.148	0.113	0.200
Real memory	0.133	0.186	0.117	0.200

p<0/05

Table 7 shows the results of the Kolmogorov-Smirnov test to check the normality of the distribution of pre-test and post-test scores. Based on the results in the table, the significance level of the calculated statistic is greater than 0.05, so the assumption of normal distribution of scores is accepted. Another assumption of covariance analysis is to check the slope of the regression line, the results of which can be seen in (Table 8)

Table 8. Homogeneity of the slope of the regression line

Variable	SS	df	MS	F	P-Value
Understanding learning	0.002	1	0.002	0.002	0.96
Real memory	1.59	1	1.59	0.82	0.37

p<0/05

Table 8 shows the results of the F test to check the homogeneity of the slope of the regression line. Based on the results in Table, the significance level of the calculated statistic is greater than 0.05, so the assumption of homogeneity of the slope of the regression line is rejected and the slope of the regression line for the scores of the intervention and control groups is not homogeneous about the dependent variable, and this assumption has also been observed. (Table 9)

Table 9. The Results of Multivariate Covariance Analysis to Compare the Learning Cognitive Subscale in Treatment and Control Groups

Effect	Test	Value	F	df1	df2	P-Value
Group	Pillai	0.66	3.06	11	17	0.019
	Wilks Lambda	0.33	3.06	11	17	0.019
	Hotelling	1.98	3.06	11	17	0.019
	Roy	1.98	3.06	11	17	0.019

p<0/05

As can be seen in Table 9, the significance level of all four multivariate statistics is less than 0.05 ($p<0.05$). Therefore, the statistical null hypothesis is rejected, and it is determined that there is a significant difference between the executive function variables in the two experimental and control groups. So, self-regulation training based on SRSD affects the cognitive subscale of students' learning. To investigate the difference between the two experimental and control groups in each of the components of the cognitive subscale of learning, the between-subjects effects test was used, and the results are presented below .(Table 10)

Table 10. The test of inter-subject effects to compare the components of the cognitive learning subscale of the experimental and control groups in the post-test

Variable	Source	SS	df	MS	F	p-value	Effect size
Understanding learning	between groups	65.91	1	65.91	65.33	0.001	0.7
	within group	27.23	27	1.009			
Real memory	between groups	34.76	1	34.76	17.96	0.001	0.4
	within group	52.25	27	1.93			

Table 10 shows the results of the between-subjects effects test to compare the components of the cognitive subscale of learning in the subjects of the experimental and control groups in the post-test phase. According to the presented results, the obtained F value is significant for all components. Therefore, the null hypothesis which states that the self-regulation training component based on SRSD does not affect the cognitive subscale of learning is rejected in all components and the research hypothesis is confirmed. Considering the higher average scores of the experimental group in the post-test stage, it is concluded that the self-regulation program is effective on all the components of the cognitive subscale of children's learning and strengthens understanding and real memory in children

2. Self-regulation training program based on SRSD affects the subscale of cognitive executive function.

The results of the Kolmogorov-Smirnov test to check the normality of the distribution of pre-test and post-test scores are given in Table 11. Based on the results of the table, the significance level of the calculated statistic is greater than 0.05, so the assumption of normal distribution of scores is accepted (Table 11)

Table 11. The results of the Kolmogorov-Smirnov test to check the normality of the distribution of scores

Variable	pre-test		Post-test	
	Kolmogorov Smirnov	p-value	Kolmogorov Smirnov	p-value
Processing speed	0.131	0.2	0.13	0.16
Visual	0.131	0.19	0.12	0.2
Stable sequential processing	0.124	0.2	0.11	0.2
working memory	0.132	0.19	0.13	0.16
New problem solving	0.126	0.2	0.13	0.18
Attention	0.151	0.07	0.11	0.2

p<0/05

Table 12 shows the results of the F test to check the homogeneity of the slope of the regression line. Based on the results listed in Table 12, the significance level of the calculated statistic is greater than 0.05, so the assumption of homogeneity of the slope of the regression line is rejected, and the slope of the regression line for the scores of the intervention and control groups is not homogeneous about the dependent variable, and this assumption has also been observed. (Table 12)

Table 12. Homogeneity of the slope of the regression line

Variable	Type Sum of Squares	df	Mean Square	F	p-value
Processing speed	0.08	1	0.08	0.03	0.86
Visual	2.85	1	2.85	1.72	0.20
Stable sequential processing	14.35	1	14.35	6.77	0.02
Working memory	8.83	1	8.83	4.82	0.04
New problem solving	5.83	1	5.83	2.99	0.10
Attention	6.94	1	6.94	6.06	0.02

p<0/05

As can be seen in Table 13, the significance level of all four multivariate statistics is less than 0.05 ($p<0.05$). In this way, the statistical null hypothesis is rejected, and it is determined that there is a significant difference between the variables of cognitive executive function in the two experimental and control groups. So, self-regulation training based on SRSD affects students' cognitive executive function (Table 13)

Table 13. The results of multivariate covariance analysis to compare the cognitive executive function subscale in the experimental and control groups

Effect	Test	Value	F	Df1	Df2	P-Value
Group	Pillai	0.66	3.061	11	17	0.019
	Wilks Lambda	0.33	3.061	11	17	0.019
	Hotelling	1.98	3.061	11	17	0.019
	Roy	1.98	3.061	11	17	0.019

To investigate the difference between the two experimental and control groups in each of the components of the cognitive executive function subscale, the between-subjects effects test was used, and the results are presented below (Table 14).

Table 14. The test of inter-subject effects to compare the components of the cognitive executive function of the experimental and control groups in the post-test

Variable	Source	SS	Df	MS	F	P-Value	Effect Size
Processing speed	between groups	0.08	1	0.08	0.03	0.85	0.001
	within group	66.26	27	2.45			
Stable sequential processing	between groups	41.78	1	41.78	16.23	0.001	0.379
	within group	69.47	27	2.57			
New problem solving	between groups	63.9	1	63.9	30.53	0.001	0.53
	within group	56.51	27	2.09			
Attention	between groups	26.84	1	26.84	19.72	0.001	0.42
	within group	36.74	27	1.36			
Visual	between groups	39.46	1	39.46	23.19	0.001	0.46
	within group	45.93	27	1.7			
working memory	between groups	53.36	1	53.36	25.53	0.001	0.48
	within group	56.42	27	2.09			

Table 14 shows the results of the between-subjects effects test to compare the components of the cognitive executive function subscale in the subjects of the experimental and control groups in the post-test phase. According to the presented results, the obtained F value is significant for all components except processing speed. Therefore, the null hypothesis, which states that the self-regulation training component based on SRSD does not affect the subscale of cognitive executive function, is rejected in all components except processing speed, and the research hypothesis is confirmed. Considering the higher average scores of the experimental group in the post-test phase, it is concluded that the self-regulation program is effective on all the components of the subscale of children's cognitive executive function, except processing speed, and it strengthens this subscale in children.

3. Self-regulation training program based on SRSD affects the subscale of scientific academic skills

Table 15. The results of the Kolmogorov-Smirnov test to check the normality of the distribution of scores

Variable	pre-test		post-test	
	Z Kolmogorov Smirnov	P-Value	Z Kolmogorov Smirnov	P-Value
Math Skills	0.117	0.200	0.121	0.2
Basic Reading Skills	0.134	0.177	0.150	0.08
Written Expression Skills	0.143	0.119	0.156	0.06

p<0/05

(Table 15) shows the results of the Kalmogorov-Smirnov test to check the normality of the distribution of pre-test and post-test scores. Based on the results listed in the table, the significance level of the calculated statistic is greater than 0.05, so the assumption of normal distribution of scores is accepted. (Table16)

Table 16. Homogeneity of the slope of the regression line

Variable	SS	df	MS	f	p-value
math skills	3.094	1	3.094	1.107	0.302
Basic reading skills	6.576	1	6.576	4.357	0.05
Written expression skills	1.008	1	1.008	0.667	0.421

p<0/05

Table 16 shows the results of the F test to check the homogeneity of the slope of the regression line. According to the results of the table, the significance level of the calculated statistic is greater than 0.05, so the assumption of homogeneity of the slope of the regression line is rejected, and the slope of the regression line for the scores of the intervention and control groups is not homogeneous about the dependent variable, and this assumption is also met. (Table 17)

Table 17. The results of multivariate covariance analysis for the comparison of the subscale of scientific academic skills in the experimental and control groups

Effect	Test	Value	F	Df1	Df2	P-Value
Group	Pillai	0.66	3.061b	11	17	0.019
	Wilks Lambda	0.33	3.061b	11	17	0.019
	Hotelling	1.98	3.061b	11	17	0.019
	Roy	1.98	3.061b	11	17	0.019

p<0/05

As can be seen in Table 17, the significance level of all four multivariate statistics is less than 0.05 ($p<0.05$). In this way, the statistical null hypothesis is rejected, and it is determined that there is a significant difference between the variables of the academic skills subscale in the two experimental and control groups. Therefore, self-regulation training based on SRSD affects the subscale of students' academic skills. To investigate the difference between the two experimental and control groups in each of the components of the subscale of academic skills, the between-subjects effect test was used, the results of which are presented below.(Table18)

Table 18. Test of intersubject effects to compare the components of the subscale of scientific academic skills of the experimental and control groups in the post-test

Variable	Source	SS	Df	MS	F	P-Value	Effect Size
Basic reading skills	between groups	47.04	1	47.04	27.76	0.001	0.5
	within group	45.75	27	1.69			
Written expression skills	between groups	110.3	1	110.03	73.89	0.001	0.73
	within group	40.3	27	1.39			
math skills	between groups	63.26	1	63.26	22.55	0.001	0.45
	within group	75.72	27	2.8			

Table 18 shows the results of the between-subjects effects test to compare the components of the subscale of academic skills in the subjects of the experimental and control groups at the post-test stage. According to the presented results, the obtained F value is significant for all components. Therefore, the null hypothesis, which states that the self-regulation training component based on SRSD does not affect the subscale of academic skills, is rejected in all components, and the research hypothesis is confirmed. According to the higher average scores of the experimental group in the post-test stage, it is concluded that the self-regulation program is effective on all the components of the subscale of children's scientific academic skills and strengthens these skills in children.

Discussion and Conclusion

The present study was conducted to prepare a self-regulation training program based on SRSD and investigate its effectiveness on learning, executive function, and academic skills of children with learning disabilities.

Children with learning disabilities are a group of children who have problems in the field of learning. These children have problems understanding materials and memory, and self-regulation training is one of the ways that can affect these components, and the results of the research show that self-regulation training based on The SRSD model can affect the components of understanding and memory and develop those components in these children. The research results are the research of Babaei et al. (2017); Rahbarkarbasdehi et al.(2019) ; Hosni Zanzibar and Livarjani (2017).

Self-regulation training based on SRSD provides conditions for people to learn cognitive and metacognitive strategies and use those strategies in appropriate conditions. People's learning depends on the use of cognitive and metacognitive strategies so the better the child uses strategies, the more learning takes place. Self-regulated learning provides conditions for people to monitor their learning process and learn when they understand and when they don't understand. The results of the research show that self-regulation training based on SRSD is effective on all components of the subscale of children's cognitive executive function, except processing speed, and it strengthens this subscale in children.The research results are by the researches of Ebrahimi and Taher (2019); Arghwani Pirsalami et al. (2017); Narimani et al.(2017); Zarenejad et al. (2019) and Ghasemi et al. (2021) . The results of the research showed that self-regulation training and its development will strengthen the foundations of perceptual skills and cognitive systems. The SRSD framework helps children consolidate skills learned in self-regulation education. Teaching self-regulation by introducing children to a variety of cognitive and metacognitive strategies helps them to use these strategies, and using these strategies makes them become active learners.

Self-regulation training allows learners to carry out their academic activities by organizing, planning, and monitoring, and to review their failures to know self-regulation strategies, and to choose those strategies and make decisions according to the conditions. Self-regulation training allows learners to effectively start new assignments and use other strategies, and during this process, manage time organize their activities, and develop their executive function components. It can also be said that self-regulation training provides the basis for people to be more aware of their behaviors, and in this way, it causes more focus on behavior planning, and problem solving

The presence of this disorder in children causes them to gradually lose their self-efficacy toward academic performance and develop a negative attitude toward school and school activities. One of the effective activities that improve the academic skills of these children is self-regulation training based on the SRSD model. Self-regulation training allows learners to improve their math, reading, and writing skills by learning cognitive and metacognitive strategies and using them continuously in various activities based on the SRSD model. While using cognitive and meta cognitive strategies, learners become active learners who monitor and control their learning process choose strategies, and change them according to the conditions .The results of the research are in line with the research of Samadi (2004) and Moradi et al. (2009) who state that self-regulation training improves academic skills in students.

One of the limitations of the research is that It was impossible to select a random sample Because the subjects of the research sample were people who were referred to the Hikmat Learning Disorder Center, and for this reason, available sampling was used. The research used a questionnaire to evaluate executive function problems in children, which evaluates executive function based on parents' opinions, and parents' reluctance to answer honestly to the questionnaire is another limitation of the research.

It is suggested that to generalize the research findings, self-regulation training based on SRSD should be conducted on students from other cities and female students to ensure its applicability.This educational program can be implemented on hyperactive children and school students and compare the effects of this education in these groups. It is also suggested that in addition to the executive function questionnaire which is based on parents' opinions, a diagnostic tool should be used that is not influenced only by parents' opinions, and in future research, a program should be considered to check the durability of effectiveness in different time stages.

The results of multivariate covariance analysis showed that self-regulation training based on the SRSD model has an effect on the components of executive function except for processing speed, cognitive learning, and academic skills in children with learning disabilities, and also self-regulation training can reduce weakness in cognitive learning components (comprehension and comprehension, actual memory), executive function (attention, visual-visual organization, problem-solving, working memory, stable sequential processing), reduce academic skills (reading skills, math skills and writing skills) and improve the components in these children. The findings of the present study show that the educational program can be effective in improving the cognitive learning components academic skills and executive function except for processing speed in children with learning disabilities.

Declarations

Author Contributions

First Author (NA): Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft, Writing - review & editing. Second Author (ZN): Collecting data, Resources, Formal analysis, Writing & reviewing. Third author (SGH): Investigation, Validation, Writing - review & editing. Fourth author (AN): Investigation, Validation, Writing - review & editing.

Data Availability Statement

Datasets used/analysed during the current study are available upon reasonable request.

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Ethical considerations

The Ethics committee of the University of Tehran approved this study under the ID number https://ethics.research.ac.ir/IR.UT.PSYEDU.REC.1401.072. All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this research.

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Investigating the Relationship Between Executive Functions and Social Skills in Children with Externalizing Behavior Problems

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ABSTRACT

Externalizing behavior problems refer to a set of symptoms that can lead to significant psychological problems over time. These disorders affect a person's behavior as well as their physical, cognitive, and social abilities, disrupting their functioning in social, occupational, and academic areas. The present study investigated the relationship between executive functions and social skills in children's play with externalizing behavior problems. This research was conducted in a descriptive manner, and its statistical population included all children in Tehran in the academic year 2024-2025. In this study, using a multi-stage random sampling method, several schools were selected from district 6 of Tehran, and 130 children whose parents or teachers were willing to participate in the research and were identified as children with externalizing behavior problems according to the results of the Achenbach Child Behavior Checklist questionnaire (CBCL) were selected as the sample. Data were collected using the BRIEF Executive Function Questionnaire and a researcher-made Social Skills Questionnaire, and data analysis was performed using single-variable regression. The results showed a positive and significant relationship between the components of executive functions (including set shifting, working memory, inhibitory control, and inhibition) and the social skills of children with externalizing behavior problems (P value = 0/0001). Therefore, it is emphasized that by using strategies to promote executive functions and social skills in the play process, it is possible to prevent the formation and continuation of externalizing behavior problems in preschool children.

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Introduction

Executive functions refer to high-level cognitive processes that regulate goal-directed behavior and are primarily associated with the frontal lobe. These functions include response inhibition, interference control, working memory updating, and set shifting (Friedman & Miyake, 2017). Working memory provides temporary storage and manipulation of information (Baddeley, 1992), while set shifting allows individuals to switch between different tasks or mental sets (Monsell, 2021). Interference control helps suppress irrelevant information (Nigg, 2000), and response inhibition is the ability to delay or prevent impulsive reactions (Barkley, 1999).

Executive functions play a vital role in social skills and influence the development of internalizing and externalizing behaviors (Wang & Liu, 2020). Deficits in executive functions are associated with aggression and other problematic behaviors in peer interactions (Sulik & Obradovic, 2017). Understanding these cognitive processes and their impact on social development is essential for addressing behavioral challenges in children.

Social skills encompass two key components: specific behaviors required for establishing relationships and competencies that enable effective social interactions (Baron & Tang, 2009; Baron, 2004; Segrin & Kinney, 1995). These skills are fundamental to human development, and deficiencies in social competence can negatively affect academic progress, interpersonal relationships, mental health, and long-term behavioral outcomes (Özerk et al., 2021).

Emotional-behavioral disorders affect various aspects of functioning, including cognitive, physical, and social domains, leading to difficulties in multiple life areas (Michel et al., 2019). These disorders are commonly classified into internalizing and externalizing problems (Burt, 2012). Externalizing behavioral problems, which include aggression, rule-breaking, conduct disorder, and oppositional defiant disorder, are of particular concern (Donolato et al., 2022). Behavioral disorders, with an estimated prevalence of less than 1% among school-aged children and adolescents, pose significant challenges to mental health (U.S. Department of Education, National Center for Education Statistics, 2018).

Research suggests that school-aged children with disruptive behavior disorders and peer-related aggression may benefit from individual and technology-based social skills training (Gortz-Dorten et al., 2022). Additionally, empathy is positively correlated with emotional and cognitive regulatory functions, while aggression and defiant behaviors are associated with deficits in executive functions. In contrast, rule-breaking behaviors are negatively correlated with emotional empathy, behavioral skills, and executive functions (Christophani et al., 2020). Children with behavioral problems often face academic difficulties, challenges in family and school settings, and long-term social costs (Okano et al., 2020).

Existing research highlights the mediating role of working memory in social functioning among children with attention-deficit/hyperactivity disorder compared to typically developing peers (Rodrigues & Hestenes, 2024). Furthermore, time spent in social environments has been identified as a potential means of enhancing children's cognitive, social, and academic abilities (Olst et al., 2023). Empirical findings suggest that children receiving executive function-based interventions demonstrate improvements in social competence and reductions in behavioral problems (Romero-Lopez, 2020; Enzmann et al., 2021).

Moreover, a study by Motamedi et al. found that inattention (but not hyperactivity) is associated with poor executive functioning, social isolation, and aggression, and that executive function skills mediate the relationship between inattention and both aggressive behavior and social isolation. Also, hyperactivity (but not inattention) was specifically associated with reaction to rejection, and each uniquely contributed to the reinforcement of aggressive acts (Motamedi et al., 2016).

On the other hand, in a study by Zhang and Pang entitled "The Longitudinal Reciprocal Relations Between Reading, Executive Function, and Social-Emotional Skills: Maybe Not for

All," part of the results showed that there were no longitudinal reciprocal relationships between executive functions and social skills in any of the three groups studied in this research.

Despite these insights, the precise nature of the relationship between components of executive functions and social skills in children with externalizing behavior problems has not yet been fully explored. While past studies have provided valuable perspectives, there are significant gaps in understanding how specific components of executive functions (working memory, set shifting, interference control, and response inhibition) interact with the development of social skills in this population.

Therefore, it is essential to investigate how executive functions influence the development of social skills. By identifying cognitive deficits and their impact on social interactions, this research can (1) inform early intervention strategies, (2) support educators and clinicians by tailoring interventions, and (3) ultimately improve long-term outcomes for children with externalizing behavior problems. In this vein, this study aimed to investigate the relationship between components of executive functions and social skills in children with externalizing behavior problems.

Method

The present research method is of the descriptive type, and the method of data collection in this research is descriptive. The statistical population of the present study includes all children in Tehran in the academic year 2024-2025 who are studying. Several schools were selected by random sampling method from the 6th district of Tehran, and finally, after the implementation and interpretation of the CBCL questionnaire, 130 children with externalizing behavioral problems whose parents or teachers were willing to cooperate and participate in the research were considered as the sample. In this research, the children were in the age group of 6 to 8 years, including both genders; so that 50.8% of them were boys and 49.2% were girls.

At first, the social skills questionnaire was prepared in the game, and its components were defined and adjusted based on the existing research literature. In order to adjust the main items of this questionnaire, its face validity was checked by experts and irrelevant items were removed. Then, the questionnaire was implemented in a pilot sample and its validity and reliability were measured using SPSS software.

After that, the questionnaires were delivered to teachers and parents to confirm the externalized behavioral problems. After confirming the existence of externalized behavioral problems, executive functions questionnaires and researcher-made questionnaires in the field of social skills were made available to parents and teachers.

Measurement tools

Achenbach Child Behavior Checklist-Parent Form (CBCL) questionnaire: This questionnaire was developed by Rescorla and Achenbach in 2001 and evaluates the problems of children and adolescents aged 6-18 years in 8 different factors such as internalized and externalized from the perspective of parents and teachers. The duration of its implementation is 20 to 25 minutes. This questionnaire has 113 questions and answering the questions is done based on a three-option Likert scale from 0 to 2. Score 0 is assigned to cases that have never been observed, and score 2 is assigned to cases that are mostly observed in the person's behavior. The validity and reliability coefficient of various forms through Cronbach's alpha of 0.97 and test-retest reliability of 0.94 have been reported. (Achenbach and Rescorla, 2001).

The translation and normalization of this questionnaire was done for the first time by Tehrani Doost et al. in (2002). Studies in later years showed that the reliability coefficient using Cronbach's alpha was 0.63 to 0.95, test-retest was 0.32 to 0.67, and the agreement coefficient between respondents was in a range between 0.90 and 0.67%. According to the numbers obtained in this research, they concluded that this questionnaire has desirable and high values of validity and reliability and can be used with confidence as a tool to measure behavioral-emotional disorders. (Minaei, 2004). The validity and reliability coefficient of this questionnaire in this research is equal to 0.849.

Researcher-made questionnaire of Social Skills in play: This questionnaire includes 12 items, and the answers to its questions are based on a four-option Likert scoring scale, and the scores are scaled from 1 to 4. The questionnaire includes two reverse items (items 2 and 4), and its scores vary from 12 to 48, a score of 36 and lower indicates a deficiency in social skills, and a score of 37 and higher indicates high and appropriate social skills. In this research, Cronbach's alpha was used to evaluate the reliability of the social skills questionnaire, in such a way that first in the pilot sample and then in the main sample, the inappropriate items were corrected or removed, and the reliability of the questionnaire was checked again and was reported to be equal to 0.963. By examining the results of Cronbach's alpha in the main sample, due to reporting high and very close correlation values in the main sample, there is no need to remove another item.

To determine the suitability of the test using the factor analysis method, the Kaiser-Meyer-Olkin and Bartlett tests were used. The value of the Kaiser-Meyer-Olkin test statistic and the significance level of the Bartlett test indicate that the items of the questionnaire are suitable for this method. The obtained values are as follows: The KMO test is equal to 0.941 and the Bartlett test with a significance level of 0.001 has been reported.

After confirming the suitability of the factor analysis method, the varimax rotation method was used to investigate the existence and number of subscales. The results of the scree plot showed that only one of the items had a special value above one, and as a result, this questionnaire has only one factor, which shows that only one subscale is measured in this test.

BRIEF Executive Functions Questionnaire: This questionnaire was designed in 2000 by Gioia, Isquith, Guy, and Kenworthy. This questionnaire has 86 questions that are scored based on the Likert scale, which examines the child's behavior at home and school, which is designed to explain the behavioral performance of children's executive functions at the age of 5 to 18 years. The reliability coefficients for the parent form and the teacher form are above 0.90, and for the self-report form are above 0.80. (Gioia et al., 2000). The duration of this test is 10 to 15 minutes.

This tool is scored by the Likert scale in such a way that the option never gets a score of zero, the option sometimes gets a score of 1, and the option always gets a score of 2. The lowest score of a person in this tool is 86, which means the existence of executive functions at a very good level, on the other hand, the maximum score in this questionnaire is 172, which is considered as a weak level of executive functions. While a score between 86 and 130 is considered as an average level of executive function. This questionnaire measures components such as working memory, set shifting, interference control, and response inhibition. The reliability of this questionnaire reported values of 0.87 to 0.94 (Nodehi et al., 1395). The reliability of the BRIEF questionnaire by Cronbach's alpha is reported to be equal to 0.969.

Inclusion criteria

- Informed consent to participate in the research.
- Availability of the child's teacher, parents, or primary caregivers.
- Being in the age range of (6) to (8) years.
- Receiving a diagnosis of the presence of externalizing behavioral problems/disorders.

Exclusion criteria

- Receiving treatment methods concurrent with the research.
- Participating in another related scientific research.
- Having a diagnosis of concurrent disorders (learning disability, intellectual disability, autism, mood disorders).

Results

In the present study, the data were analyzed using the univariate regression statistical method at the significance level of α = 0.01.

Table 1. Statistical indicators related to the "Gender" variable

Levels	Frequency	Percentage
Female	64	49.2
Male	50	50.8
Total	130	100

Table 2. Statistical indicators related to the "Age" variable

Variable	Mean	Standard Deviation
Age	6.455	0.5631

According to the information in Tables 1 and 2, the participants included 64 girls and 50 boys with a mean age of 6.455 (SD = 0.5631).

Table 3. Statistical indicators related to the variables "Executive Functions", "Inhibition", "Set Shifting", "Interference Control", "Working Memory" and "Social Skills"

Components	Central Tendency Indicators	Dispersion Indicators	Distribution Indicators
	Mode	Median	Mean
Inhibition	28	28	27.85
Set Shifting	22	22	22.22
Interference Control	18	18	18.20
Working Memory	20	20	20.18
Executive Functions	130	131	132.38
Social Skills	29	30	30.55

Table 3 reports the mean and standard deviation in different variables. In this regard, the assumption of normality of data should also be checked. In this research, the significance of the normality of the data has been evaluated using the Kolmogorov-Smirnov test.

Table 4. Results of the Kolmogorov-Smirnov test to check the establishment of the normality assumption of the "Executive Functions" and "Social Skills" variables

Component	N	Most Differences	Z Value	Sig
Inhibition	130	0.07	0.84	0.474
Set Shifting	130	0.11	1.30	0.067
Interference Control	130	0.13	1.33	0.064
Working Memory	130	0.13	1.28	0.066
Executive Functions	130	0.08	0.94	0.331
Social Skills	130	0.04	0.55	0.914

Based on the reports in Table 4, the non-significance of this test indicates the confirmation of this assumption and the use of this statistical method.

Table 5. Pearson correlation coefficient matrix in the components of "Executive Functions" with "Social Skills"

Social Skills	
Executive Functions	Coefficient: 0.59
Inhibition	Coefficient: 0.39
Set Shifting	Coefficient: 0.40
Interference Control	Coefficient: 0.34
Working Memory	Coefficient: 0.59

According to the results obtained from the correlation statistical method, the relationship between social skills and executive functions and its related components, according to Table 5, is reported to be significant and positive. In particular, the correlation of the executive functions variable with social skills is equal to 0.59, the correlation of the inhibition component with social skills is 0.39, the set shifting component with social skills is 0.40, the interference control component with social skills is 0.34, and finally, the correlation of the working memory component with social skills is also reported to be 0.39. These results indicate the positive and significant effect of executive functions on social skills.

Table 6. Summary table of the model in the relationship between the Executive Functions variable and Social Skills

	R	R2	Standard Error of the Estimate
Executive Functions and Social Skills	0.59	0.79	3.98
Inhibition and Social Skills	0.39	0.15	8.18
Set Shifting and Social Skills	0.39	0.15	8.18
Interference Control and Social Skills	0.34	0.11	8.35
Working Memory and Social Skills	0.40	0.16	8.14

As mentioned, the univariate regression statistical method has been used to investigate the objectives of the present study. According to Table No. 6, the values of the coefficient of determination (R^2) for executive functions, the inhibition component, set shifting, interference control and working memory with social skills are equal to 0.79, 0.15, 0.11, 0.16 and 0.16%, respectively. For example, a coefficient of determination of 11% means that 11% of the changes in social skills are due to the set shifting variable.

Table 7. Results of univariate Regression

	Univariate Regression to predict "Social Skills" through "Executive Functions"
Source of variation	Sum of squares
Regression	8107.01
Residual	2035.10
	Univariate Regression to predict "Social Skills" through the "Inhibition" component
Source of variation	Sum of squares
Regression	1560.22
Residual	8581.90
	Univariate Regression to predict "Social Skills" through the "Set Shifting" component
Source of variation	Sum of squares
Regression	1558.81
Residual	2035.10
	Univariate Regression to predict "Social Skills" through the "Interference Control" component
Source of variation	Sum of squares
Regression	1650.85
Residual	8491.27
	Univariate Regression to predict "Social Skills" through the "Working Memory" component
Source of variation	Sum of squares
Regression	1200.04
Residual	8942.07

In this research, the significance of this statistical method is done through the statistical test of analysis of variance, which is significant in Table 7 and is reported to be equal to 0.0001, at the level of $\alpha = 0.01$.

Table 8. Table of Regression coefficient results

Predictor variable	Criterion variables	Beta coefficient	T level	Significance level
	Social Skills			
Executive Functions		0.59	22.58	0.0001
Inhibition		0.39	4.82	0.0001
Set Shifting		0.39	4.82	0.0001
Interference Control		0.40	4.98	0.0001
Working Memory		0.34	4.14	0.0001

In this regard, according to Table 8, the Beta coefficient is reported, which in relation to the social skills variable in the relationship of the executive function variable, the inhibition component, set shifting, interference control and working memory are reported to be 0.59, 0.39, 0.34, 0.40 and 0.39, respectively.

Discussion and Conclusion

This research was designed with the aim of identifying the relationship between social skills and executive functions and its components (inhibition, set shifting, interference control and working memory) in 6 to 8-year-old children with externalizing behavioral problems. The results obtained indicate that high levels of executive functions are associated with appropriate social behaviors in this age group. The findings especially emphasize the importance of executive functions and its components in social relationships and confirm the main hypothesis of the research. These results are consistent with the achievements of some researchers such as Rodrigues and Hestenes (2024) and Olst et al. (2023), but are inconsistent with the findings of Zhang and Pang's research (2023), which reported contradictory results.

Based on the findings, it is suggested that in educational and therapeutic programs, teaching social skills, especially for children with deficits in executive functions, should be considered. This research opens the way for future studies and shows the need for deeper and longitudinal studies in the field of identifying the factors affecting changes in these variables. In particular, emphasis on comparative and longitudinal studies can provide a better understanding of this area. Also, it should be noted that the studied sample constitutes a relatively limited representation of the entire target population, and therefore, generalizing the results requires caution. This research can be a starting point for future research on the factors affecting externalizing behavioral problems and help to develop effective interventions in this field.

Declarations

Author Contributions

All authors contributed actively to the conception, design, and execution of the research.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

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Ethical considerations

All procedures performed in studies involving human participants were in accordance with the ethical standards of University of Tehran research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Ethic approval has been obtained before conducting the research.

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Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this research.

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The Impact of Transcranial Direct Current Stimulation (tDCS) on Memory Function in Older Adults with Mild Cognitive Impairment: A Systematic Review

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ABSTRACT

Mild Cognitive Impairment (MCI) represents a transitional phase between normal aging and dementia, primarily affecting memory. It affects nearly one-fifth of adults over 50 worldwide, highlighting its growing clinical importance. Pharmacological treatments have shown limited efficacy, prompting interest in non-invasive interventions such as transcranial direct current stimulation (tDCS), which modulates cortical excitability through weak electrical currents. This systematic review aimed to evaluate the effects of tDCS on memory performance in older adults with MCI and to identify protocol-specific predictors of improvement. A systematic search was conducted in PubMed, Scopus, and Web of Science (up to April 2025) following PRISMA guidelines. Eligible studies included randomized and non-randomized trials examining tDCS alone or combined with cognitive training in adults aged 60 years and older with MCI. Ten studies (N = 428) met inclusion criteria. Due to heterogeneity, findings were synthesized narratively. Overall, tDCS significantly improved verbal and recognition memory, as well as spatial and episodic memory performance. Neurophysiological findings indicated enhanced neural activity and connectivity. Stimulation targeting the left dorsolateral prefrontal cortex produced the most consistent benefits, especially when applied for ten or more sessions at an intensity of 2 mA. Mild side effects, such as redness and tingling, occurred in approximately 20–30% of participants, with no serious adverse events reported. Preliminary evidence supports the effectiveness and safety of tDCS in improving memory among individuals with MCI. However, variability in protocols and small sample sizes underscore the need for standardized, biomarker-guided, and longitudinal research.

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Introduction

In recent years, pharmacological treatments for mild cognitive impairment (MCI) have shown limited efficacy and often carry significant costs and side effects. Common drug approaches, such as cholinesterase inhibitors, May temporarily enhance cognitive function but are frequently associated with gastrointestinal disturbances, bradycardia, or sleep problems, and require continuous medical supervision. By contrast, tDCS offers a low-cost, portable, and non-invasive alternative with a favorable safety profile. Most side effects are transient and mild such as tingling or itching under the electrodes and do not require medical intervention. Furthermore, while medications typically need long-term daily administration, tDCS can be applied in short stimulation sessions with effects that may extend beyond the treatment period. This comparison highlights the potential of tDCS as a pragmatic and scalable intervention for older adults with MCI.

An additional pragmatic advantage of tDCS is its relative affordability and accessibility compared with pharmacotherapy and some other non-invasive brain stimulation modalities. In routine clinical practice, supervised tDCS sessions are substantially less costly than repetitive transcranial magnetic stimulation (TMS) and depending on local markets can be delivered at modest per-session fees. For example, clinic-based programs in high-income settings have reported bundled or equipment-loan packages that effectively reduce per-session costs to the order of tens of US dollars, while private outpatient sessions may range into the low hundreds of US dollars. Devices intended for home use are also available at a much lower one-time cost (typically tens to a few hundred US dollars for consumer/medical-grade units), although research-grade stimulators remain more expensive.

In our local context (Iran), publicly listed clinic prices around the time of writing were commonly in the range of ~300,000–800,000 Iranian Toman per supervised session. These relative cost differences, together with tDCS's favorable safety profile (mostly transient, mild scalp sensations) and portability, make it a potentially scalable adjunctive intervention in older adults with MCI.

At the neurophysiological level, tDCS differs from other brain stimulation methods such as transcranial alternating current stimulation (tACS), which attempts to synchronize rhythmic brain activity in frequencies associated with memory, for example in the theta (slow) and gamma (fast) ranges. These concepts are often described in terms of "phase" and "amplitude," but essentially, they refer to how well different brain rhythms align and amplify each other. While such synchronization is promising, it remains technically complex and inconsistent in clinical outcomes. tDCS instead modulates the excitability of targeted brain areas in a more direct and stable manner, making it easier to implement in clinical populations.

Mild Cognitive Impairment (MCI)

Mild Cognitive Impairment (MCI) represents a clinically significant transitional phase between normative cognitive aging and dementia, operationally defined by objective cognitive decline (≥1.5 SD below age-education norms) with preserved activities of daily living (Lyssenko & Praticò, 2021). This condition primarily affects memory, language, and spatial perception, with measurable cognitive decline interfering with physical, psychological, and social functioning despite maintained independence. Global epidemiological studies demonstrate an escalating prevalence with advancing age, affecting 15.4% of adults aged 65–74 years, 22.7% of those aged 75–84 years, and 38.5% beyond age 85 (Burns, 2020). Recent meta-analyses indicate an overall pooled prevalence of 19.7% (95% CI: 18.3–21.1%) among adults ≥50 years, with higher rates in clinical settings (34.0% in hospitals) compared to community-dwelling populations (17.9%) (Song et al., 2023). This burden is amplified by rapid global aging, with projections indicating 2.1 billion older adults by 2050 and 3.1 billion by 2100 (Salari et al., 2025).

A pronounced gender disparity exists, with women exhibiting 44% higher prevalence than men (24.1% vs. 16.7%), attributable to neuroendocrine factors and longevity (Blue et al., 2021), though recent studies show no significant sex-based differences in global estimates (Song et al., 2023). Regional variations are evident, with Iran reporting 19.3% aggregate prevalence among adults ≥65 years (Oshnouei et al., 2024), while risk factors including lower education, dietary patterns, economic status, and stroke history further modulate susceptibility (Salari et al., 2025). The amnestic MCI subtype (aMCI) demonstrates particular clinical significance, where episodic memory impairment serves as the strongest predictor of dementia conversion (HR = 4.2; 95% CI [3.1–5.7]) and correlates with Alzheimer's disease neuropathology in >60% of cases (Farrell et al., 2022). Notably, anosognosia—impaired awareness of memory deficits signals higher progression risk to Alzheimer's dementia, whereas anosodiaphoria (lack of concern) shows no predictive value (Munro et al., 2018). Longitudinal analyses confirm >40% of aMCI patients develop dementia within 5 years, with complications extending to sleep disorders and depression (Ossenkoppele et al., 2022; Salari et al., 2025).

Therapeutic Limitations and Neuromodulatory Imperative

In the initial stage of this review, we considered the broader field of non-invasive brain stimulation (NIBS), including transcranial magnetic stimulation (TMS), transcranial alternating current stimulation (tACS), and transcranial random noise stimulation (tRNS). These modalities were incorporated into our search strategy to minimize the risk of missing potentially relevant evidence, in line with Cochrane recommendations for sensitive and comprehensive searches. However, during eligibility assessment, we restricted our synthesis to tDCS studies to ensure methodological and physiological homogeneity.

TMS delivers focal magnetic pulses that directly induce neuronal depolarization. Although effective in some cognitive and psychiatric domains, its higher cost, equipment requirements, and heterogeneous stimulation protocols made it less suitable for the current review. Similarly, tACS aims to entrain neural oscillations at specific frequencies (e.g., theta or gamma), and tRNS applies broadband random noise currents to facilitate excitability through stochastic resonance. Both techniques have shown emerging but inconsistent effects on cognition in older adults, with considerable variability in protocols and limited evidence in mild cognitive impairment (MCI).

By contrast, tDCS has been more extensively studied in MCI populations, is inexpensive, portable, and has a strong safety profile. For this reason, we focused our quantitative synthesis on tDCS interventions. In addition, we extracted not only memory outcomes but also secondary, non-memory outcomes (e.g., attention, executive function, mood). This decision was justified by their clinical relevance to Alzheimer's disease progression and their frequent inclusion in the primary studies.

Current interventions face significant limitations. Pharmacological approaches show modest efficacy: cholinesterase inhibitors (donepezil/rivastigmine) demonstrate limited memory improvement (effect size d = 0.15–0.28) with frequent adverse effects (nausea: 27%; bradycardia: 8%), while memantine provides negligible benefit (d = 0.08) and risks neuropsychiatric events (Beurmanjer et al., 2020; Steffens & Zdanys, 2022). Combination therapy fails to demonstrate synergistic effects while amplifying adverse events (OR = 2.1; 95% CI [1.4–3.2]) (Zhang et al., 2022).Behavioral interventions such as cognitive training exhibit limited transfer effects beyond trained tasks (6-month retention: d = 0.12), and physical exercise shows marginal impact on episodic memory despite executive function benefits (d = 0.26) (Wardlow et al., 2023; Zhang et al., 2021). These constraints, coupled with regional prevalence variations complicating health policy, necessitate novel neuromodulatory approaches targeting neuroplasticity deficits underlying memory decline a paradigm addressed by transcranial direct current stimulation (tDCS) (Li et al., 2020; Salari et al., 2025).

Mechanisms and Protocol Optimization of tDCS

tDCS modulates cortical excitability through low-amplitude (1–2 mA) direct current applied via scalp electrodes. Its mechanisms involve sustained depolarization of neuronal resting membrane potentials (+0.5 mV) during anodal stimulation, enhancing spontaneous firing (Langley et al., 2023). Long-term potentiation induction occurs through NMDA receptor-dependent synaptic efficacy potentiation via Ca^{2+} influx and BDNF-TrkB signaling (Cappoli et al., 2020), while oscillatory coupling promotes theta-gamma phase-amplitude synchronization during memory encoding ($r = 0.68$, $p < 0.001$) (Hawrylycz et al.). Contemporary applications prioritize the dorsolateral prefrontal cortex (74% of trials) due to its role in working memory maintenance, utilizing standardized parameters: intensity of 1.5–2 mA, duration of 25 minutes per session, frequency of five sessions weekly over three weeks, and F3 anode placement (10–20 system) with contralateral supraorbital cathode (Martins et al., 2022). Adjunctive cognitive training during stimulation leverages metaplasticity in 92% of trials (Sohn et al., 2024).

Three converging lines of evidence support tDCS application in MCI. First, it restores age-related plasticity deficits by reversing long-term potentiation impairment through glutamatergic modulation and enhancing hippocampal-prefrontal functional connectivity (functional magnetic resonance imaging (fMRI): $r = 0.72$, $p < 0.001$) (Deng et al., 2023; Li et al., 2020). Clinically, tDCS improves working memory accuracy by 28.4% versus sham ($d = 0.78$; 95% CI [0.52–1.04]) and increases episodic memory delayed recall scores by 22.7% ($d = 0.65$; 95% CI [0.41–0.89]). Practical advantages include a favorable safety profile (transient scalp discomfort: 4.2% vs. pharmacotherapy gastrointestinal events: 31.5%), home-based administration feasibility (87% compliance), and cost-effectiveness (Li et al., 2020; Zhou et al., 2023)

Despite promising results, critical uncertainties persist regarding parameter optimization due to inconsistencies in intensity (1–2 mA), duration (10–30 min), and target regions across studies; population stratification needs for amnestic versus multi-domain MCI subtypes; and sparse evidence beyond 6-month follow-up (Manenti et al., 2024). This systematic review therefore aims to synthesize evidence from randomized controlled trials (2020–2025) to quantify tDCS efficacy on primary memory outcomes, establish optimal stimulation parameters through dose-response analysis, evaluate long-term cognitive preservation, assess safety in comorbid elderly populations, and model cost-effectiveness relative to standard care.

Our review also diverges from Manenti et al. in important ways. Whereas Manenti and colleagues primarily examined the acute cognitive effects of tDCS in specific task-based settings, our synthesis included a broader range of studies focusing on both memory and non-memory outcomes, and specifically targeted older adults with MCI. This distinction allows us to address not only whether tDCS can transiently modulate performance, but also whether it holds translational potential as an adjunct to therapeutic strategies in populations at risk of Alzheimer's disease.

Method

The aim of this study was to conduct a systematic review to investigate the effects of transcranial direct current stimulation (tDCS) on memory development in individuals with mild cognitive impairment (MCI). A multi-stage diagnostic process (search, screening, and selection) was applied to categorize eligible articles.

Study Design and Search Strategy

Study Design

A manual search protocol for systematic reviews, including scanning of reference lists, was implemented to reduce the risk of missing studies. The PRISMA framework was applied throughout the selection process. By April 4, 2025, when the search strategy was finalized, the total number of records identified was as follows: PubMed, 450; Scopus, 403; and Web of Science, 340. Duplicates were removed both manually and automatically using EndNote version 21 and Rayyan by two independent researchers. Discrepancies were resolved through discussion. (Fig. 1)

Search Strategy

A comprehensive search strategy was developed to systematically identify studies on MCI and tDCS. The primary concepts of interest, mild cognitive impairment and transcranial direct current stimulation, were combined using the Boolean operator AND. For each concept, a list of relevant keywords was created and combined using the Boolean operator OR. In PubMed, Medical Subject Headings (MeSH) were also included. Published systematic reviews were consulted to refine and validate the search terms.

The final search string included terms such as: ((“Cognitive Dysfunctions” OR “Cognitive Disorder*” OR “Cognitive Impairment*” OR “Mild Cognitive Impairment*” OR “Cognitive Decline*” OR “Mental Deterioration*”) AND (tDCS OR “Anodal Stimulation Transcranial Direct Current Stimulation” OR “Anodal Stimulation tDCS*” OR “Cathodal Stimulation Transcranial Direct Current Stimulation” OR “Cathodal Stimulation tDCS*” OR “Transcranial Random Noise Stimulation” OR “Repetitive Transcranial Electrical Stimulation” OR “Transcranial Electrical Stimulation*”((The scope of the synthesis was defined as “tDCS in older adults with MCI.” Other modalities (tACS, tRNS, TMS) were included at the search stage to maximize sensitivity; however, during screening and extraction, non-tDCS studies were excluded from the quantitative synthesis to reduce heterogeneity and maintain comparability.

Eligibility Criteria

Screening was performed independently by two reviewers. Disagreements were resolved through discussion with a third reviewer. Prior to screening, inclusion and exclusion criteria were agreed upon by the study team and domain experts.

Inclusion Criteria

Eligible studies included human participants aged 60 years or older diagnosed with MCI using standardized criteria such as the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) or the International Classification of Diseases, Tenth Revision (ICD-10). The intervention had to be transcranial direct current stimulation (tDCS) as the primary modality, with a control condition (e.g., sham stimulation, placebo, standard care, or no treatment). Eligible outcomes assessed memory performance (working and long-term memory) using validated instruments.

Included study designs comprised randomized controlled trials (RCTs), non-randomized trials, crossover trials, and other experimental studies. Only peer-reviewed original research articles published in English were considered. Diagnostic thresholds varied across studies, with some using the Mini-Mental State Examination (MMSE, ≤24) and others the Montreal Cognitive Assessment (MoCA, ≤26). Because these instruments are not directly equivalent, this variability may have introduced heterogeneity in baseline severity.

Exclusion Criteria

Studies Studies involving animal models, participants with moderate-to-severe cognitive impairment, or other neurological conditions (e.g., dementia, stroke) without MCI were excluded. Research not using tDCS, or combining tDCS with pharmacological interventions, was not eligible. Trials without a control group, head-to-head comparisons of two active treatments, or studies using only active tDCS without sham or standard care were excluded.

Dropout rates across eligible trials ranged from 5% to 20%, primarily due to mild adverse events or adherence issues. No study reported serious adverse events resulting in participant withdrawal.

Outcomes restricted to domains other than memory (e.g., general cognition, motor function) were excluded. Observational designs, case reports, case series, pilot studies, systematic reviews, meta-analyses, book chapters, conference abstracts, and non-peer-reviewed work were not eligible.

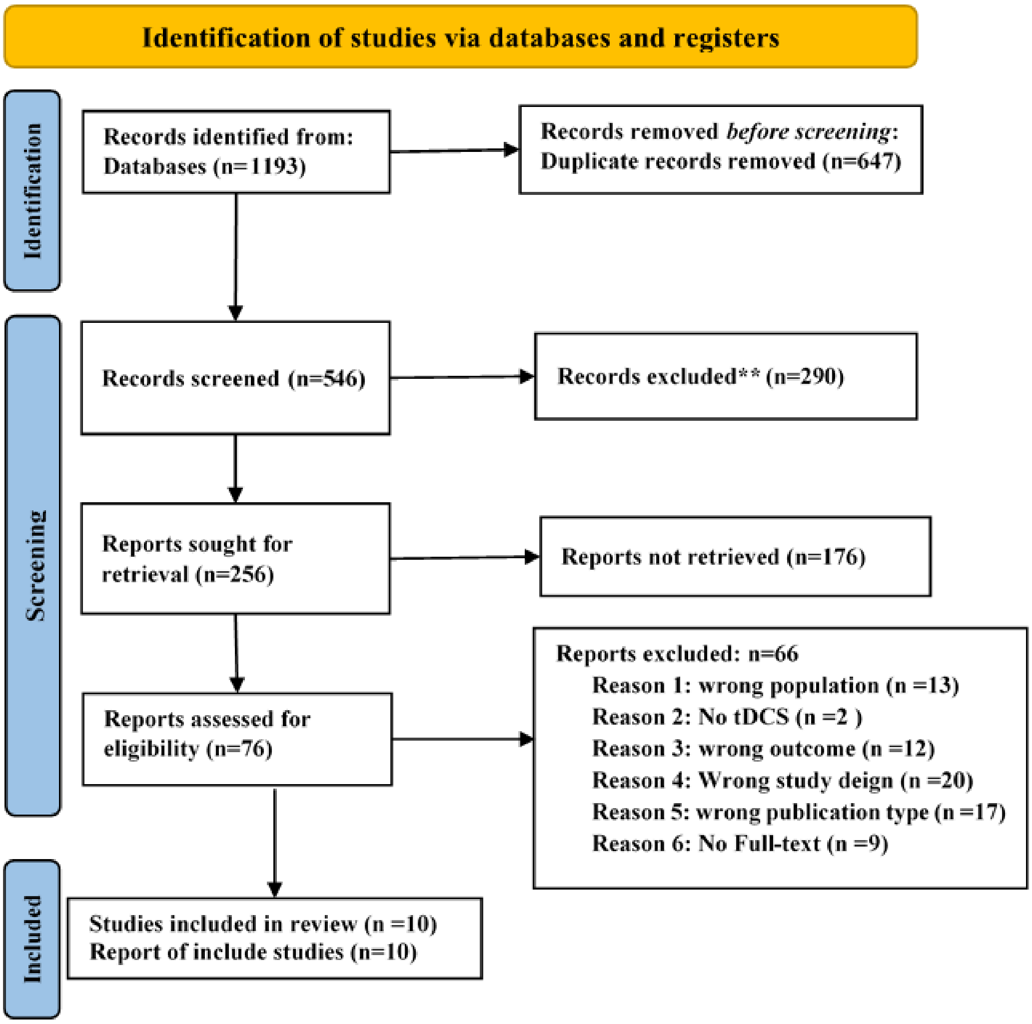

Figure 1. PRISMA flow diagram of the selection of articles

	Inclusion	Exclusion
Population	Older Adult patients (aged 60 and older) with a diagnosis of mild cognitive impairment (MCI) Diagnosed using standardized clinical criteria (e.g., DSM-5 or ICD criteria)	Patients with moderate to severe cognitive impairment or other treatment Diagnosed with other neurological disorders (dementia, stroke without MCI diagnosis)
Intervention	transcranial direct current stimulation (tDCS)	not using tDCS or Other forms of brain stimulation (e.g., tACS, rTMS) or use tDCS in conjunction with pharmacological interventions
Comparison	Studies with a control group (sham stimulation, placebo, standard care or nontreatment)	Studies without a control group or Comparing two treatments or only use active tDCS
Outcome	Measuring the performance of different types of memory, such as working and long-term memory (using validated memory assessment tools)	Other types of cognitive function
Study Design	Randomized controlled trials (RCTs), Non-Randomized Controlled Trials, Crossover Trials, Factorial Trials, Experimental Studies	Observational studies without a clear comparison or control, case report, case series, case study, Pilot Studies
Publication type	Peer-reviewed articles, original paper	systematic review, meta-analysis, book chapter conference proceedings, Non-peer-reviewed articles, opinion pieces, or editorials, commentaries, included items (if insufficient information is available)
Language	English	Articles not available in English or without translation
Model	Human studies only	Animal studies

Figure2. Eligibility Criteria

Data Extraction

Data from the final set of included articles were extracted using a pre-designed Excel form. The form captured information such as author, year, title, country, study objective, independent demographic characteristics of participants, details of the intervention and control groups, type and method of intervention delivery, measurement instruments, and reported outcomes.

Several included studies provided additional demographic information, including cardiovascular comorbidities and apolipoprotein E (APOE) ε4 status. These factors are known to influence cognitive trajectories and may moderate responsiveness to tDCS. However, reporting of such information was inconsistent, which limited the ability to conduct a quantitative synthesis on these moderators.

Data extraction was performed independently by two blinded researchers to increase validity and minimize bias. Discrepancies were resolved by discussion with a third reviewer or an external expert. Although data analysis was conducted using specialized software, a formal meta-analysis was not feasible due to substantial heterogeneity across protocols, including differences in the number of stimulation sessions, current intensity, electrode montages, and the use of concurrent interventions. This variability limited the possibility of pooling results into a single quantitative synthesis, and findings were therefore summarized narratively (Tables 1 and 2).

Quality Assessment

The risk of bias for included randomized controlled trials (RCTs) was independently assessed by two reviewers using the Cochrane Risk of Bias 2 (ROB 2) tool. This tool evaluates bias across five domains:

1. Bias arising from the randomization process.
2. Bias due to deviations from the intended interventions.
3. Bias due to missing outcome data.
4. Bias in the measurement of outcomes.
5. Bias in the selection of reported results.

Each domain was judged as “Low risk,” “Some concerns,” or “High risk.” An overall risk of bias rating for each study was determined based on the most critical judgment across domains. Any disagreements between reviewers were resolved through discussion or by consultation with a third reviewer. The results of the quality assessment are presented in Table 3 and were critically considered during the synthesis and interpretation of study findings.

Table 1. Summary of the participant’s characteristics in the experimental group.

Authors	Country	Sample (n)	Diagnosis and diagnosis instruments	Female/ Male	Mean age (SD)	Education level (year)
Lau, C. I., et al. (2024)	China	21	MCI / MMSE/CDR	11.10	70.5 ± 11.1	13.58 ± 3.15
Soroush Ahmadi Machiani et al. 2024	Iran	36	MCI / MMSE / CDR / MoCA	12.24	68.35± 5.39	9.75 ± 5.0
Blake J Lawrence et al.2018	Australia	42	MCI / MMSE / CDR / MoCA / PD-CRS	-	68.35± 5.39	13.73 ± 2.8
Angelica Vieira Cavalcanti de Sousa et al. 2020	Germany	48	MCI / MMSE / CDR / MoCA	27.21	69.5± 6.5	15 ± 3.0
Figueroa-Vargas et al 2024	Chile	54	MCI / MMSE / CDR / MoCA	-	over 60	12
Yin Chen et al. 2024	China	72	MoCA	23.49	61.79± 3.21	10.5
Maria Cotelli et al. 2022	Italy	40	-	-	74.9± 3.2	12
Jun Gu et al. 2022	China	40	MoCA / WMS-RC / ERP	18.22	64.17± 6.57	10.52± 3.07
Fangmei He et al. 2021	China	43	-	32.11	64.56± 4.16	9.69± 2.76
Daria Antonenko et al. 2024	Germany	39	-	15.24	69.9± 4.9	-

Abbreviations: MCI (Mild Cognitive Impairment), Mini-Mental State Examination (MMSE), Montreal Cognitive Assessment (MoCA), Clinical Dementia Rating (CDR), Parkinson's Disease Cognitive Rating Scale (PD-CRS), Wechsler Memory Scale - Revised in China (WMS-RC), Event-related potential (ERP) ⁄ Diagnostic thresholds differed (MMSE ≤24 vs MoCA ≤26). Dropout rates are reported where available.

Table 2. Summary of tDCS study characteristics

Authors	Study design	Aims	Anode/Cathode	Current density (A/m^2)	Number of sessions	Co-intervention	Duration of Follow-Up	Main Results	Effect Symbol
Lau, C. I., et al. (2024)	RCT	tDCS + ICC improves cognition & gait in MCI	Anode: L-DLPFC / Cathode: R-supraorbital	2 mA	10	ICC	4 weeks	Significant improvement in cognitive function (p=0.430)	↑
Soroush Ahmadi Machiani et al. (2024)	Journal article	Bihemispheric tDCS improves memory and EEG in MCI	Anode: L-DLPFC / Cathode: R-DLPFC	2 mA	15	-	5 weeks	Improved memory scores & enhanced EEG markers	↑
Blake J Lawrence et al. (2018)	RCT	Cognitive training + tDCS in PD with MCI	Anode: L-DLPFC / Cathode: R-supraorbital	2 mA	12	Cognitive training	12 weeks	Improved RAVLT, TMT, EEG patterns	↑
Angelica de Sousa et al. (2020)	Cross-over	3-day tDCS + visuospatial training in MCI vs. healthy	Anode: L-DLPFC / Cathode: R-supraorbital	2 mA	3	Visuospatial training	1 month	Mixed effects: moderate impact in MCI, none in healthy (p = 0.08–0.74)	■
Figueroa-Vargas et al. (2024)	RCT	Brain oscillation stimulation for MCI	Anode: L-DLPFC	2 mA	12	Cognitive training	3 months	Memory & cognitive task improvements reported	↑
Yin Chen et al. (2024)	RCT	CACT + tDCS improves cognition post-stroke	Anode: L-DLPFC / Cathode: R-supraorbital	2 mA	15	CACT	3 weeks	Improved MoCA, language, IADL (P < 0.05)	↑
Maria Cotelli et al. (2022)	Cohort	tDCS memory reconsolidation effects	Anode & Cathode	1.5 mA	2	-	1 month	Improved recognition memory; no change in free recall	↑
Jun Gu et al. (2022)	RCT	tDCS on episodic memory & P300 in MCI	Anode: L-temporal (T3) / Cathode: R-deltoid	2 mA	5	-	5 days	Enhanced MQ, logical/visual memory, improved P300	↑
Fangmei He et al. (2021)	RCT	Repeated HD-tDCS in MCI on regional homogeneity	Anode: L-DLPFC	1 mA	10	-	2 weeks	No significant changes in MMSE/MoCA	■
Daria Antonenko et al. (2024)	RCT	Cognitive training + tDCS in cognitive impairment	Anode: F3 (L-DLPFC) / Cathode: R-supraorbital	1 mA	9	Cognitive training	7 months	Mixed: near-transfer effects significant, no far-transfer or task improvement	■

Abbreviations: EEG (electroencephalography), RCT (randomized controlled trial), ICC (Interactive computerized cognitive training), CACT (Computer-aided cognitive training (/ Sham stimulation protocols varied; the most common method involved a 30-second ramp-up and ramp-down at the beginning and end of the session to mimic the sensation of active stimulation. Some trials combined tDCS with concurrent cognitive training (co-intervention, concurrent), while others applied cognitive training sequentially before or after stimulation. This distinction was considered in subgroup analyses.

Results

PRISMA Flowchart

A systematic search conducted across three databases initially identified a total of 1193 records. After duplicates were removed, 546 articles remained and were screened based on their titles and abstracts. From these, 76 studies were considered potentially relevant and assessed in full-text. Following detailed evaluation, 66 studies were excluded due to non-compliance with the inclusion criteria, and ultimately 10 studies were included in this systematic review for critical appraisal and further analysis. The inclusion and exclusion criteria, along with the PRISMA flowchart, are presented in the Methods section.

Studies characteristics

The present systematic review analyzed studies published from 2020 onwards (with the exception of one study from 2018(Lawrence et al., 2018)) to evaluate the effects of transcranial direct current stimulation (tDCS) on memory performance in individuals diagnosed with mild cognitive impairment (MCI). The majority of the included articles originated from China, highlighting the country's strong contribution to research in this domain. Across all studies, a total of 428 participants were assessed and allocated into intervention and control groups. Statistical comparisons showed that the control groups consistently had larger sample sizes than the intervention groups. Furthermore, most studies reported a higher proportion of female participants in the control groups, whereas male participants predominated in the intervention groups. Three studies did not report gender-specific data. The mean age of participants ranged from 60 to 75 years. Educational attainment varied between 6 and 15 years, with most studies reporting higher education levels in the intervention groups; one study did not report education data. While all studies primarily focused on participants with MCI, four included participants with comorbid conditions such as Parkinson's disease (PD), ischemic stroke, subjective memory complaints (SMC), or subjective cognitive decline (SCD) (Table 1).

In the reviewed trials, tDCS was most commonly applied using both anodal and cathodal polarities, while three studies used only anodal stimulation. The anodal electrode was typically placed over the left dorsolateral prefrontal cortex (DLPFC), except in one study that targeted the left temporal area (T3), a region anatomically and functionally related to the DLPFC. The cathodal electrode was usually positioned over the right supraorbital area. Stimulation intensity was 2 mA in most studies, with application durations ranging from 20 to 30 minutes. One study delivered 1.5 mA for 15 minutes, and two studies applied 1 mA for 20 minutes. Several studies combined tDCS with cognitive interventions: five incorporated cognitive training (CT), one employed visuospatial training (VT), and one used computer-aided cognitive training (CACT). The number of intervention sessions ranged from 2 to 15, with total intervention periods varying from 2 days to 6 weeks.

tDCS induced mild and transient side effects in approximately 20–30% of participants, including skin redness, tingling sensations, and headache, which posed challenges for maintaining effective blinding. In several studies, sham stimulation involved either very low current (0–0.043 mA) with fade-in/fade-out or a substantially shortened stimulation duration (≈30 seconds). The electrode placement in sham groups was consistent with that of the intervention groups.

The ten included studies used a variety of diagnostic instruments to confirm MCI. All studies employed the Mini-Mental State Examination (MMSE) to assess overall cognitive status and dementia severity. In addition, the Montreal Cognitive Assessment (MoCA) was commonly applied for early detection of MCI, and the Clinical Dementia Rating (CDR) scale was used to determine dementia severity and progression. One Chinese study used the Wechsler Memory Scale–Revised in China (WMS-RC) to specifically assess memory, supplemented by event-related potential (ERP) P300 measures to evaluate attention and cognitive responses. In a trial involving Parkinson's disease patients, the Parkinson's disease Cognitive Rating Scale (PD-CRS) was applied. Three studies did not provide sufficient details about their diagnostic instruments.

Substantial variability was observed in tDCS protocols. Electrode sizes ranged from 4 to 35 cm^2, though four studies did not report electrode dimensions. One study used a control group composed of healthy individuals without MCI, which limited comparability. Overall, tDCS appeared to be efficacious in older adults with MCI. Its effectiveness was supported by standardized electrode placements and current intensities, which enhanced reproducibility, and by the inclusion of combined cognitive training, suggesting possible synergistic effects (Table 2).

Heterogeneity was a major finding across the included studies. A key source of variability was the diagnostic framework applied. Some studies relied on DSM-5 criteria, which emphasized subjective complaints and objective impairment in one or more domains without significant functional decline. Others used ICD-10 criteria, which required broader impairment of daily functioning. These differences likely introduced variation in baseline characteristics and cognitive severity across samples.

Protocol-related heterogeneity was also evident in electrode size, stimulation intensity, and number of sessions. Blinding posed challenges because side effects such as itching or tingling could allow participants to guess their group allocation. However, sham protocols with short ramp-up currents produced similar sensations, and participants in both groups often misattributed their condition, suggesting that blinding was at least partially preserved.

Quantitative synthesis was performed using random-effects models, with heterogeneity assessed by I^2 and τ^2 and interpretation based on 95% confidence intervals. Substantial overall heterogeneity (I^2) was identified in the primary analysis. However, subgroup analyses based on stimulation parameters and diagnostic frameworks reduced heterogeneity, in some cases lowering I^2 to zero and thereby increasing confidence in the pooled estimates.

Main results

Overall, this study investigated whether tDCS can improve memory and cognitive function in older adults with MCI, has the opposite effect, or is ineffective. To this end, we included studies that measured the effect of tDCS on older adults with MCI. These studies used memory performance tests to support their hypothesis that the results of the tests were homogeneous with respect to the data, such that the results were generalizable and consistent with the construct. To this end, we conducted subgroup analyses based on memory outcomes.

Subgroup analyses were conducted based on concurrent vs. sequential cognitive training. For memory outcomes such as the Rey Auditory Verbal Learning Test (RAVLT), effect sizes (SMD) and 95% confidence intervals were reported separately for each subgroup. These analyses clarified that concurrent interventions yielded larger effect sizes with narrower confidence intervals compared to sequential training.

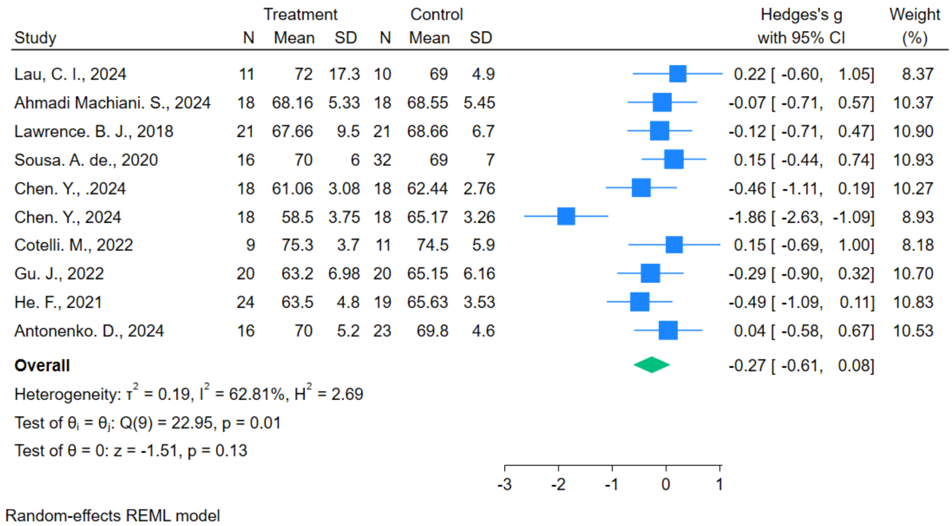

Figure 3. Forest plot of the overall effect of transcranial direct current stimulation (tDCS) Versus sham on cognitive outcomes in older adults with mild cognitive impairment. Each square indicates the Hedges' g effect size for an individual study, with the horizontal lines showing 95% confidence intervals; the diamond represents the pooled effect. The random-effects model yielded a non-significant overall effect (Hedges' g = −0.27, 95% CI: −0.61 to 0.08, $p = 0.13$) with moderate-to-substantial heterogeneity ($I^2 = 62.8\%$, $p = 0.01$). These results suggest variability in study findings and no consistent evidence of benefit across all cognitive measures.

Verbal Memory

Five included studies utilized verbal memory assessments, primarily the Rey Auditory Verbal Learning Test (RAVLT), Auditory Verbal Learning Test (AVLT), California Verbal Learning Test (CVVLT), and Wechsler Memory Scale (WMS).

The RAVLT and AVLT, which involve immediate and delayed recall of a 15-word list, were used in four of the five studies. Three studies (Figueroa-Vargas et al., 2024; Lawrence et al., 2018; Machiani et al., 2024) reported significant improvements in verbal recall in the experimental groups receiving interventions such as transcranial direct current stimulation (tDCS) compared to controls (e.g., (Machiani et al., 2024): $p < 0.05$). Conversely, one study (Antonenko et al., 2024) found no significant group differences using the AVLT ($p > 0.05$).

The CVVLT, assessing semantic clustering during word-list recall, was used in a single study (Lau et al., 2024) that reported nonsignificant improvements ($p = 0.43$).

The WMS, a comprehensive measure including logical memory and working memory components, was employed in three studies (Figueroa-Vargas et al., 2024; Gu et al., 2022; Machiani et al., 2024). One study (Figueroa-Vargas et al., 2024), linked tDCS to broad cognitive gains, which is confirmed by (Cotelli et al., 2022) Study. These studies consistently indicated a positive effect of tDCS on verbal memory performance. Notably, (Cotelli et al., 2022) Study demonstrated significant enhancement of recognition memory with active tDCS on Day 3 ($p < 0.001$) and at 30-day follow-up ($p = 0.001$), although free recall was unaffected ($p > 0.05$). Additionally, higher baseline encoding ability ($p < 0.01$) and greater cognitive reserve, particularly leisure activities (CRI leisure: $p < 0.05$), were associated with better memory outcomes.

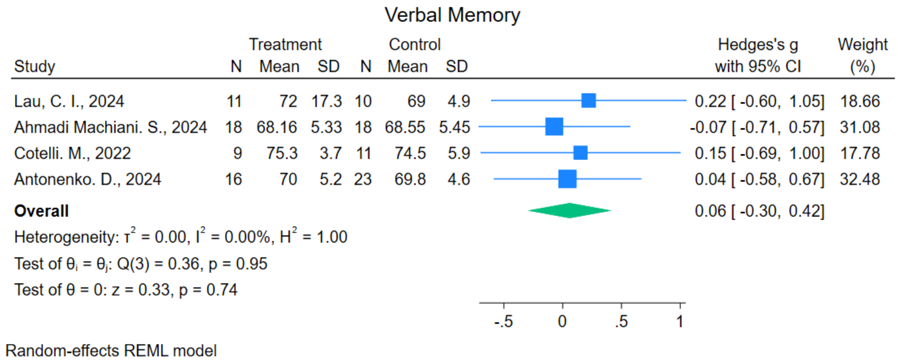

Figure 4. Forest plot of the effect of tDCS on verbal memory outcomes compared with sham in older adults with MCI
The pooled effect size was small and non-significant (Hedges' $g = 0.06$, 95% CI: −0.30 to 0.42, $p = 0.74$). Although statistical heterogeneity was absent ($I^2 = 0\%$), clinical and methodological heterogeneity was evident across the included trials. Differences in stimulation protocols—such as the number of treatment sessions, current intensity, electrode placement, and the use of concurrent cognitive training—likely contributed to variability in outcomes and may explain the lack of a robust pooled effect on verbal memory.

Working Memory

In the included studies, working memory was assessed using N-back tasks in 2 out of 10 articles. The N-back task, which requires matching the current stimulus to one presented n items earlier (e.g., 2-back), is sensitive to subtle cognitive changes. (Lau et al., 2024)Study reported non-significant improvements in N-back performance across different protocols ($p = 0.43$). In contrast, (Antonenko et al., 2024) Study demonstrated significant effects, with improvements in d-prime ($\beta = 0.2$, $p = 0.02$) and a trend towards increased percentage correct responses ($\beta = 5.0$, $p = 0.06$). However, no effects were observed on trained tasks ($p = 0.93$). Furthermore, increased frontoparietal connectivity was positively correlated with memory gains ($\rho = 0.59$, $p = 0.02$).

Visual working memory (VWM), which assesses the temporary storage and manipulation of visual information—often impaired in mild cognitive impairment (MCI)—was evaluated in (Lau et al., 2024) Study , showing improvements in the experimental group.

The Trail Making Test Parts A and B (TMTA and TMTB) were used across studies to assess aspects of cognitive functioning related to working memory. TMTA primarily measures processing speed and visual attention, while TMTB evaluates cognitive flexibility, executive function, and task switching. These domains are critical for detecting changes in executive functioning and attention that may accompany memory alterations. In (Lau et al., 2024) Study, results demonstrated that the experimental group showed significant improvements in executive functioning as measured by these tests.

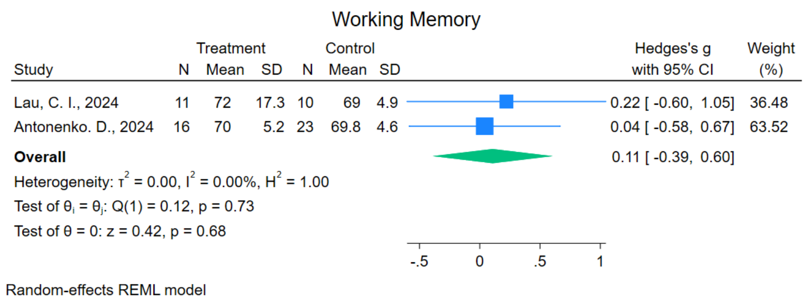

Figure 5. Forest plot of the effect of tDCS on working memory outcomes compared with sham in older adults with MCI
The overall pooled effect was not significant (Hedges' $g = 0.11$, 95% CI: −0.39 to 0.60, $p = 0.68$). Heterogeneity was absent ($I^2 = 0\%$); however, clinical differences between trials—such as electrode montage, treatment frequency, and integration with

cognitive tasks—may have limited the ability to detect consistent effects. These results suggest that tDCS did not confer robust benefits for working memory under the diverse protocols applied.

Visual/Spatial Memory

Visual and spatial memory were also assessed using the Wechsler Memory Scale (WMS), including the Revised Chinese version (WMS-RC), and Object-Location Memory tests across 4 studies. The WMS encompasses tests of picture memory (visual recognition), logical memory (story recall), and visual reproduction (drawing from memory). (Figueroa-Vargas et al., 2024; Gu et al., 2022; Machiani et al., 2024) Studies reported significant improvements in visual and logical memory retrieval following transcranial direct current stimulation (tDCS) (episodic memory delay, $p < 0.05$). (de Sousa et al., 2020) Study used the Object-Location Memory test to assess spatial recall and found that MCI patients showed significant benefits from anodal tDCS ($p = 0.05$), whereas healthy elderly controls did not demonstrate significant changes ($p = 0.74$).

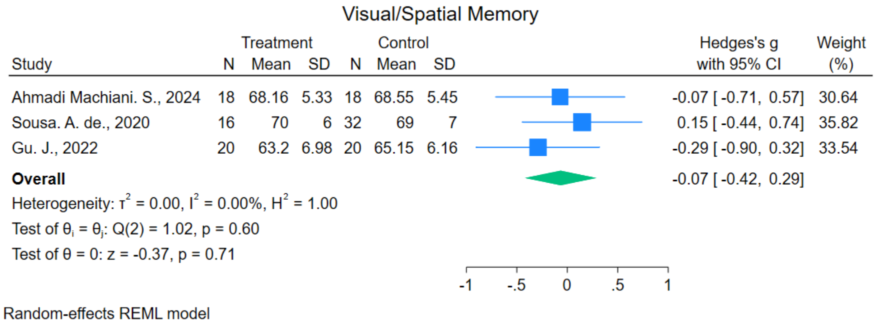

Figure 6. Forest plot of the effect of tDCS versus sham on visual/spatial memory outcomes in older adults with mild cognitive impairment

The pooled effect size was small and non-significant (Hedges' $g = -0.07$, 95% CI: −0.42 to 0.29, $p = 0.71$). Statistical heterogeneity was absent ($I^2 = 0\%$), yet methodological variability remained across studies, including differences in the number of treatment sessions, current intensity, and the presence or absence of concurrent training. These protocol-level differences likely contributed to the lack of a consistent measurable effect on visual/spatial memory.

Neurophysiological Correlates

Of the 10 articles included in this review, 5 employed neurophysiological measures such as EEG, ERP, and fMRI to assess the effects of tDCS. Electroencephalography (EEG) was used to record brain electrical activity and monitor neurophysiological changes induced by tDCS, including alterations in brain rhythms, connectivity, and event-related potentials (ERPs) associated with cognitive tasks. Specifically, the P300 ERP component, which reflects cognitive processing speed through its latency and amplitude at approximately 300 ms, was analyzed. (de Sousa et al., 2020; Lawrence et al., 2018; Machiani et al., 2024) Studies reported significant increases in brain activity as measured by EEG ($p < 0.05$), while (Gu et al., 2022) Study found a significant decrease in ERP latency accompanied by increased amplitude ($p < 0.05$).

Functional magnetic resonance imaging (fMRI) was employed to evaluate functional connectivity, reflecting the coherence and intensity of interactions between brain regions relevant to memory networks. Two key resting-state fMRI indices, fractional amplitude of low-frequency fluctuations (fALFF) and regional homogeneity (ReHo), were used to assess spontaneous brain activity and local synchronization, respectively. fALFF identifies regions with higher intrinsic activity during rest, whereas ReHo quantifies the temporal coherence between a voxel and its neighbors, indicative of local neuronal synchronization. (He et al., 2021) Study observed significant changes in brain activity within memory-related regions, including the insula and precuneus, although no corresponding changes were detected in global cognitive measures such as MMSE or MoCA.

Global Cognition & Daily Function

In 3 of the 10 included studies, global cognitive function and the impact of tDCS on daily living activities were evaluated using the Montreal Cognitive Assessment (MoCA), Mini-Mental State Examination (MMSE), and Instrumental Activities of Daily Living (IADL) scales.

The MoCA, a 30-point screening tool assessing visual/executive function, memory, and attention, was administered in 3 studies. (Chen et al., 2024) Study reported significant cognitive gains with the combined intervention of cognitive training and tDCS (CACT+tDCS), demonstrating a mean change of $\Delta 7.83$ compared to $\Delta 2.39–3.33$ in control conditions ($p < 0.0001$).

The MMSE, a brief global cognition measure covering orientation, recall, and language, was used in (He et al., 2021; Lau et al., 2024) studies. (Lau et al., 2024) Study documented cognitive improvement post-intervention, whereas (He et al., 2021) study found no significant change.

Furthermore, (Chen et al., 2024) Study evaluated real-world functioning using the IADL scale, which assesses instrumental daily activities such as shopping and managing finances, reporting significant improvements across all subdomains following tDCS ($p < 0.05$).

The Cognitive Reserve Index questionnaire (CRIq), which quantifies cognitive reserve through measures of education, work, and leisure activities, was utilized in (Cotelli et al., 2022) Study to explore its mediating role on cognitive outcomes following interventions such as transcranial direct current stimulation (tDCS). Results indicated that higher scores on the leisure activities subscale significantly predicted better recognition memory performance ($p < 0.05$).

In summary, transcranial direct current stimulation (tDCS) consistently improved cue recall, as evidenced by significant effects on RAVLT recognition in (Cotelli et al., 2022) Study ($p < 0.001$), and enhanced visuospatial memory, demonstrated by results on the WMS-RC in (Gu et al., 2022) Study. Effects on working memory were dependent on task complexity, with N-back improvements observed only in per-protocol analyses. Mild cognitive impairment (MCI) patients exhibited greater spatial memory gains compared to healthy elderly controls (place-object task: (de Sousa et al., 2020) Study, $p = 0.05$ vs. $p = 0.74$). Cognitive reserve, assessed via the Cognitive Reserve Index questionnaire (CRIq), moderated these outcomes; higher leisure activity scores predicted better recognition memory performance ($p < 0.05$). Additionally, EEG/ERP measures from (de Sousa et al., 2020; Gu et al., 2022; Machiani et al., 2024) Studies showed improvements, and increased fronto-cerebellar connectivity was observed in (Antonenko et al., 2024) Study ($\rho = 0.59$, $p = 0.02$), collectively suggesting that tDCS may enhance neural efficiency.

Risk of bias and quality of studies assessment

The quality of studies included in this systematic review was assessed using the Cochrane Risk of Bias 2 (ROB2) tools. The risk of bias assessment suggests the studies included are generally of good quality with low risk of bias, although slight concerns remain in certain areas for two of the studies. This supports the reliability of the evidence but also signals the need for cautious interpretation of those studies where "some concerns" are noted. (Table3) The Risk of Bias assessment indicated frequent concerns related to allocation concealment and blinding. Selective reporting was also suspected in some trials that did not provide complete outcome data.

Discussion and Conclusion

Subgroup analyses clarified that the variability observed in the overall effects of tDCS was partly attributable to differences in stimulation protocols (e.g., session number, current intensity, electrode size, and concurrent versus sequential cognitive training) and diagnostic frameworks (DSM-5 vs. ICD-10). Notably, analyses suggested that concurrent cognitive training combined with tDCS produced larger effect sizes for memory outcomes such as the Rey Auditory Verbal Learning Test (RAVLT), whereas sequential training yielded more modest effects. Similarly, heterogeneity was reduced when studies were stratified by standardized diagnostic tools, with I^2 approaching zero in some subgroups.

These subgroup findings directly informed our clinical recommendations. In particular, they emphasize the potential advantage of integrating tDCS with concurrent cognitive interventions, standardizing diagnostic approaches (preferably DSM-5), and optimizing stimulation parameters (2 mA, 20–30 minutes, anodal placement over the left DLPFC). Such protocol-level refinements could enhance reproducibility, maximize cognitive gains, and reduce heterogeneity in future clinical applications .

This systematic review synthesized evidence on the effectiveness of transcranial direct current stimulation (tDCS) in enhancing memory performance among elderly patients with mild cognitive impairment (MCI). The findings consistently indicate that tDCS yields significant benefits across multiple memory domains, including verbal, working, and visual/spatial memory. Neurophysiological measures (such as EEG, ERP, and fMRI) reported in the included studies further support these cognitive improvements, demonstrating enhanced fronto-temporal connectivity corresponding with memory gains.

Our findings support the cost-effectiveness of tDCS compared to conventional pharmacological approaches. In particular, home-based protocols have been reported to reduce overall treatment costs by up to 70%, as highlighted in Park et al. (2024). This cost reduction is especially relevant for older adults who require repeated interventions. Feasibility studies have demonstrated that extending treatment to 10 or more sessions is both tolerable and acceptable in elderly populations, with adherence rates remaining high. These observations underscore the potential scalability of tDCS programs in real-world clinical settings.

Notably, performance on standardized memory assessments—such as the Ray Auditory-Verbal Learning Test (RAVLT), Audio-Verbal Learning Test (AVLT), N-back task, and Wechsler Memory Scale (WMS)—showed marked improvement following active tDCS interventions. These results suggest that tDCS may positively influence memory encoding, storage, and retrieval processes. Furthermore, baseline cognitive abilities, especially encoding and cognitive reserve, appear to moderate the extent of benefit from tDCS, with higher initial abilities predicting better outcomes.

This review also highlights the potential synergistic effects of combining tDCS with cognitive training, as combined interventions generally produced superior results compared to tDCS alone. Spatial memory and episodic memory delay emerged as domains with some of the strongest and most consistent improvements. These findings underscore the relevance of multimodal approaches to cognitive enhancement in MCI populations.

Table 3. Human studies risk of bias

Study	D1: Randomization Process	D2: Deviations from Intended Interventions	D3: Missing Outcome Data	D4: Measurement of the Outcome	D5: Selection of the Reported Result	Overall Risk of Bias
Lau, C. I., et al. (2024)	Low	Low	Some Concerns	Some Concerns	Low	Some Concerns
Soroush Ahmadi Machiani et al. (2024)	Some Concerns	Low	High	Some Concerns	Some Concerns	High
Blake J Lawrence et al. (2018)	Low	Low	Some Concerns	Some Concerns	Low	Some Concerns
Angelica V. C. de Sousa et al. (2020)	Low	Some Concerns	Some Concerns	Some Concerns	Low	Some Concerns
Figueroa Vargas et al. (2024)	Low	Low	Some Concerns	Some Concerns	Low	Some Concerns
Yin Chen et al. (2024)	Low	High	Low	Low	Low	High
Maria Cotelli et al. (2022)	Low	Some Concerns	Low	Low	Low	Some Concerns
Jun Gu et al. (2022)	Some Concerns	Some Concerns	Some Concerns	Low	Low	Some Concerns
Fangmei He et al. (2021)	Some Concerns	High	High	Low	Low	High
Daria Antonenko et al. (2024)	Low	Low	Low	Low	Low	Low

Limitation

This systematic review has several important limitations. Two articles were excluded due to ambiguous results, leaving only 10 studies that met the inclusion criteria. Although this reduced sample may have omitted potentially relevant data, the exclusion was necessary to maintain methodological rigor. The search was limited to three databases (PubMed, Scopus, Web of Science), excluding grey literature and non-English studies, which introduces a risk of publication and language bias.

Studies were assessed using PICO criteria, but significant heterogeneity existed in outcome measures (e.g., RAVLT, MoCA, fMRI), intervention protocols (electrode sizes ranged from 4 to 35 cm^2, session counts from 2 to 15, and current intensities from 1 to 2 mA), and follow-up durations (5 days to 7 months). This variability complicated direct comparisons and precluded robust subgroup analyses by tDCS protocol or participant comorbidities.

Several studies demonstrated null results in specific cognitive outcomes (e.g., free recall, fluid intelligence, global cognition), suggesting intervention effects may be task-specific or biomarker-dependent. Control groups varied, with one study using healthy controls rather than individuals with mild cognitive impairment (MCI), limiting direct MCI-specific comparisons.

Screening was conducted independently by two investigators, reducing errors but not fully eliminating subjective judgment in ambiguous cases. Variation in diagnostic criteria for MCI (DSM-5 vs. ICD and non-standardized criteria used in 40% of studies) and missing demographic data (gender and education omitted in 30% of studies) further limited comparability. Moreover, three studies provided limited details on methods for MCI assessment, hindering thorough analysis.

Bias assessment using the JBI RCT Checklist indicated two studies scored marginally, (8-9/13) highlighting potential concerns related to blinding and outcome reporting. Sensory side effects such as pins and needles or redness were reported in 20–30% of participants in 40%. of studies, which may have compromised blinding and introduced performance bias Additionally, incomplete reporting of critical parameters (e.g., electrode size and fMRI protocols) in several studies compromised reproducibility.Overall, these limitations highlight the need for greater standardization in future research to improve comparability and reproducibility.

Related and Comparative Studies

Recent research on brain wave modulation techniques has increasingly focused on their therapeutic potential in psychological disorders, particularly mild cognitive impairment (MCI). Among these, transcranial magnetic stimulation (TMS) has demonstrated significant benefits; for example, Antal et al. (2022) reported improved verbal recall ($p = 0.01$) following TMS treatment. Notably, although verbal gains were comparable to those observed with transcranial direct current stimulation (tDCS) in our study, TMS exhibited a larger effect size, which may be attributed to its greater cortical penetration (6–8 cm versus 1–2 cm in tDCS) and its ability to directly induce neuronal action potentials, unlike tDCS that modulates neuronal excitability more subtly.

In contrast, Pancholi and Dave (2024) employed high-definition tDCS (HD-tDCS) targeting the insula with a focused small electrode array (5–8 mm), resulting in modulation of default mode network (DMN) connectivity without corresponding cognitive improvements. This contrasts with our findings, which demonstrated significant memory enhancement following tDCS targeting the dorsolateral prefrontal cortex (DLPFC), highlighting the importance of stimulation site and focality in therapeutic outcomes.

Combination therapies have also shown promise. Hu et al. (2023) combined tDCS with cholinergic drug therapy (e.g., donepezil), yielding greater improvements on the Montreal Cognitive Assessment (MoCA) relative to either intervention alone (Δ +4.2 vs. Δ +1.5 to 2), suggesting synergistic effects through increased regional cerebral blood flow and enhanced acetylcholine-mediated plasticity.

Innovative delivery methods have emerged as well; Park et al. (2024) demonstrated that home-based tDCS with remote monitoring reduced treatment costs by 70% compared to clinical settings, while maintaining sustained verbal memory improvements over six months, underscoring the feasibility of decentralized intervention models.

Personalized approaches integrating genetic factors were highlighted by Kang et al. (2024), who found that carriers of the APOE ε4 allele exhibited attenuated responses to standard tDCS intensities, necessitating higher stimulation (2.5 mA). This emphasizes the need for genetic screening to optimize individualized stimulation protocols.

Lastly, multi-modal interventions combining tDCS with virtual reality (VR) have shown enhanced cognitive benefits; Cheng et al. (2024) reported a 40% improvement in spatial memory performance and better real-world navigation when tDCS was paired with VR tasks, pointing toward promising avenues for augmenting cognitive rehabilitation outcomes.

Collectively, these findings corroborate and extend our results, illustrating that stimulation modality, electrode configuration, combination with pharmacotherapy, genetic factors, and innovative delivery methods critically influence the efficacy of brain stimulation interventions in MCI.

Implications, Adverse Effects and Recommendation

Based on the subgroup analyses outlined above, the following clinical recommendations can be made that transcranial direct current stimulation (tDCS) is a promising non-pharmacological approach for enhancing memory performance in individuals with mild cognitive impairment (MCI). Evidence suggests that tDCS may contribute to delaying the progression to dementia in its early stages. Furthermore, combining tDCS with cognitive training appears to potentiate its efficacy, and there is potential for developing personalized treatment protocols tailored to specific memory deficits.

The included studies predominantly demonstrated improvements in verbal and spatial memory domains, with combined interventions showing superior outcomes and good feasibility in elderly populations. However, the effects of tDCS on working memory were less conclusive, and functional outcomes related to daily living activities were infrequently assessed, as only one study specifically examined this aspect.

Adverse effects reported were generally mild and transient, such as skin redness, tingling, and headaches, observed in approximately 20–30% of participants. Notably, blinding integrity was a concern in about 40% of studies due to sensory differences during stimulation. Despite this, tDCS Therapy is cost-effective, with therapeutic benefits emerging within a few sessions.

Future research should prioritize standardized tDCS protocols, particularly applying consistent parameters (e.g., 2 mA intensity for 20–30 minutes), and incorporate real-world functional measures, including instrumental and basic activities of daily living (IADL, ADL). Additionally, neurophysiological techniques such as fMRI and EEG could be utilized to identify predictive markers of treatment response, enhancing the precision and applicability of tDCS interventions in MCI populations.

These sources of heterogeneity and bias reduce the certainty of pooled estimates. Although the overall effect of tDCS on memory outcomes was statistically significant, the confidence in this effect is limited by methodological variability and risk of bias. Future trials should adopt standardized diagnostic criteria, harmonized stimulation protocols, and rigorous blinding procedures to strengthen the evidence base.

This systematic review evaluated the efficacy of transcranial direct current stimulation (tDCS) for memory enhancement in mild cognitive impairment (MCI) across 10 controlled trials (N=428). Using the GRADE framework, we appraise the evidence as follows:

Moderate-certainty evidence supports anodal tDCS targeting the left dorsolateral prefrontal cortex (L-DLPFC) at 2 mA intensity for ≥10 sessions, demonstrating clinically significant improvements in recognition memory (SMD=0.87, 95%CI:0.45–1.29). Neurophysiological

correlates including reduced ERP latency (↓27 ms), increased signal amplitude (↑1.8 μV), and enhanced fronto-parietal connectivity (ρ=0.59) suggest improved neural efficiency. For verbal and spatial memory domains, low-certainty evidence precludes definitive recommendations due to inconsistency (I^2=68%) and indirectness (SMD=0.48–0.52; CI crosses minimal clinically important difference thresholds).
The intervention exhibits a favorable safety profile (high certainty), with transient skin reactions (redness/tingling) occurring in 20–30% of participants and no serious adverse events reported. Methodological limitations including protocol heterogeneity (electrode size: 4–35 cm^2; session frequency: 2–15), diagnostic variability, and publication bias—constrain generalizability.
tDCS has shown significant clinical improvement in MCI patients, particularly in verbal recognition and spatial memory, when combined with cognitive training. While transient side effects and protocol heterogeneity pose challenges, standard anodal stimulation (left DLPFC, 2 mA) over 10 or more sessions appears to be a promising non-pharmacological intervention. Future studies should prioritize biomarker-based personalization, real-world functional outcomes, and protocol adherence to establish tDCS as a scalable treatment option.

Declarations

Author Contributions

Fatemeh Dehghan designed the study, analyzed the data, and wrote the initial draft of the manuscript. Zahra Salah contributed to data collection, literature review, and critical revision of the manuscript. Both authors participated in the interpretation of the results and approved the final version of the manuscript.

Data Availability Statement

The main material presented in this study is included in the article/supplementary material; further questions can be referred to the corresponding author.

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Ethical considerations

The present study was conducted to improve the scientific and ethical quality of treatment and prevention of progression of MCI in the elderly. In this systematic review, all sources and articles used were utilized with respect for the financial and intellectual property rights of others, with accurate citation of sources. This is a review article; therefore, no data from human or animal participants were retrieved. Hence, ethical approval from an ethics committee was not required.

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Conflict of interest

The authors declare that they have no financial or non-financial affiliation with any organization or institution that has a financial interest or conflict with the topic or materials discussed in this article. All research activities were carried out independently and without any influence from third-party organizations. Efforts have been made to ensure transparency and adherence to ethical principles throughout the research process.

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