Fostering Physics Comprehension in Secondary School Students

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Fostering Physics Comprehension in Secondary School Students

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Abstract

Science's pivotal role in advancing human civilization underscores its significance. Metacognition —-understanding how we think about our thinking –proves pivotal in achieving groundbreaking discoveries in science. Achieving this requires robust metacognitive skills to observe and reconcile conflicting theories and data to derive meaningful conclusions. While there has been considerable exploration of metacognition within the broader context of scientific inquiry, limited research has been conducted to understand metacognition in secondary school science education. This experimental study investigates the impact of metacognitive intervention on adolescents' conceptual understanding of Newton's laws of Force and Motion. It employs a thought experiment framework, guiding participants to reflect on phenomena related to force and motion through various representations. In this process, participants, with or without metacognitive interventions, made predictions using an independent object perspective in the pre-training and a first-person physical experience during the bodily training phase. Additionally, it explores correlations between individual metacognitive abilities and learning outcomes. Surprisingly, the findings contrast prior research involving adults, revealing that secondary school participants (*N* = 36) did not exhibit improved learning outcomes with metacognitive support. Furthermore, only minimal correlations emerged between their metacognitive skills and learning outcomes. In response to these unexpected results, this study concludes by offering practical recommendations for optimizing metacognitive support tailored to secondary school science education. These

insights offer valuable guidance to educators and researchers aiming to enhance the effectiveness of metacognitive interventions in this educational context.

Dedication

To my better half, Harald,

This thesis would not have seen the light without your unwavering support.

With love and gratitude,

Eugene

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Chapter I.

Introduction

The progress of human civilization is intricately tied to our knowledge of the world. Specifically, science has played a significant role in advancing civilization by applying scientific knowledge to meet essential human needs and elevate overall quality of life. The COVID-19 vaccination, for instance, not only safeguarded countless lives but also released the world from lockdowns, restoring normalcy where people could resume their daily activities. Furthermore, science is frequently viewed as a catalyst for enhancing a country's economic wellbeing and national competitiveness in the world. Recently, in August 2023, India surprised the world by successfully landing its lunar lander, Chandrayaan-3, on the Moon. This historic event marked India as the fourth nation to achieve a successful moon landing and the first to do so in the Moon's South Pole region. This accomplishment highlights India's scientific and technological advancements, which outpace its current economic position as a developing nation. In this context, there is a widespread anticipation that the country will enhance its economic status in the near future.

The success of India's achievement and the hopeful future it envisions can be attributed to the solid foundation of scientific knowledge and research established by generations of scientists throughout history. The endeavor of launching a lunar lander relies on a blend of advanced scientific understanding and practical expertise, a legacy that has evolved throughout human history, during which there have been important breakthroughs such as Newton's theory of how celestial bodies move in the universe and the gravitational forces governing these movements.

Many people commonly believe that Newton serendipitously found the idea of universal gravity through his observation of an apple falling from a tree. However, it is clear that the revelation of such an intricate concept was not a mere coincidence. The seemingly straightforward event involved a rigorous scientific process that demanded highly developed metacognitive abilities. Upon witnessing an apple falling from the tree, he posited that the force responsible for the apple's fall could also account for the motion of celestial bodies throughout the universe. By drawing parallels between his observation and his theory, he was able to incorporate his existing knowledge into questions that could be empirically investigated through the measurement of observable phenomena. Subsequently, he translated specific patterns observed in the orbital movements of planets and satellites into supporting evidence for his argument about universal gravity. He reached conclusions by employing a series of metacognitive processes that encompassed inferences and deductions based on his hypotheses, analysis of collected empirical data, and his theoretical understanding. The scientific method he utilized in this procedure transformed data into considerably more informative evidence compared to the hypothetico-deductive model, which was predominantly employed by earlier scientists and depended solely on hypotheses and deductive reasoning (Harper, 2011).

The progress of scientific knowledge and research in history has played a crucial role in improving the quality of life, both at the individual and national levels. However, as illustrated in Newton's story, scientific discoveries and breakthroughs do not occur through casual inquiry. The key factor in effectively turning an inquiry into meaningful learning and updating our comprehension of science lies in the presence of robust metacognitive abilities. Acknowledging the importance of science, countries around the world boosted their research investments by 19.2% from 2014 and 2018 (Nair-Bedouelle, 2021). This growth rate surpasses the 14.8% increase in global GDP during the same period, underscoring the prioritization of scientific advancement. However, there is still limited research exploring the role of metacognition on successful scientific investigation and the utilization of metacognitive abilities in science education. This gap in research is particularly pronounced when it comes to the secondary school demographic, which has received relatively little attention.

Metacognition in Learning

Metacognition is commonly described as “thinking about one’s thinking”, and it has received various definitions from scholars due to its intricate nature. Defining metacognition in the context of learning presents an even greater challenge because learning itself is a complex process. Nevertheless, it is clear that metacognition is vital to learning because thinking about one’s own thinking seems to be a fundamental element of the learning process. One example of using metacognition during learning is the explicit comparison of one’s prior understanding of a phenomenon with new incoming information, where the new information may or may not be consistent with the prior understanding.

In broader terms, metacognition can be defined as an individual’s ability to be aware of and control their learning process (Baker & Brown, 1984; Brown, 1978; Flavell, 1979). According to Brown (1978), metacognition involves activities such as planning, problem-solving, understanding one’s thought processes, and organizing thoughts. This definition encompasses being conscious of how one learns, setting and achieving goals, applying knowledge in the face of challenges, assessing cognitive demands, understanding strategies relevant to objectives, and evaluating one's performance. Although the concept of metacognition undeniably encompasses an intricate interrelationship between cognitive and emotional aspects, some scholars have endeavoured to classify metacognition into specific domains. This categorization aids in gaining deeper insights into the cognitive processes, especially concerning successful learning.

Flavell (1979) introduced a classification of metacognition into two primary elements: metacognitive knowledge and metacognitive experiences. Metacognitive knowledge encompasses three key variables: personal knowledge, task knowledge, and strategy knowledge. Metacognitive experiences include feelings of comprehension and can serve as the impetus for strategy implementation. Personal knowledge entails evaluating one's own learning capabilities and recognizing the factors that influence learning outcomes. Task knowledge involves a learner's understanding of the objectives, characteristics, and requirements of learning tasks. Strategy knowledge, on the other hand, pertains to understanding various strategies, which can be highly advantageous in achieving learning goals and empowering learners to make informed choices regarding the most suitable strategy for their needs.

Brown (1978) outlined metacognition as comprising two components: knowledge of cognition and regulation of cognition. Knowledge of cognition pertained to what individuals understand about their cognitive processes, facilitating their reflections on their thinking. Regulation of cognition constitutes a series of actions aimed at helping learners in managing and overseeing their learning processes. This aspect encompasses three fundamental metacognitive skills: planning, monitoring and evaluation.

Although both frameworks take slightly different approaches to the concept of metacognition, they underscore two fundamental aspects of metacognition. Firstly, they both highlight the prominence of self-awareness in the context of learning, referring to it as metacognitive knowledge in Flavell's framework and knowledge of cognition in Brown's framework. Despite the differing terminology, both frameworks emphasize the significance of individuals comprehending and being conscious of their own learning abilities. Secondly, they both stress the importance of regulatory components in learning. Brown explicitly dissects them as planning, monitoring, and evaluation, while Flavell focuses on the broader idea of regulation involving the formulation and implementation of strategies in learning.

Understanding the significance of self-awareness and regulation within the learning process holds important implications for how robust metacognition can enhance learning outcomes and how we can enhance the learning experience. Strong metacognition empowers learners to monitor and control their cognitive processes effectively, leading to more efficient and adaptive learning strategies. By fostering self-awareness, individuals can recognize their strengths and weaknesses, enabling them to tailor their approach to learning to suit their specific needs. Additionally, improved regulation of cognition means learners can set goals, plan strategies, monitor progress, and evaluate the effectiveness of their learning methods, ultimately optimizing their learning experiences. In practical terms, this knowledge can inform educators and learners alike on the importance of metacognitive skills in achieving educational goals and can guide the development of strategies and interventions to promote more effective and meaningful learning.

Metacognition in Science Education

The importance of metacognition becomes more evident in the context of science education, especially within contemporary secondary school curricula that emphasize scientific inquiry as the principal approach to learning science (National Research Council., 2000). In essence, students are encouraged to build new scientific knowledge through a structured process that involves observation, hypothesis formation, prediction, experimentation, and result analysis to draw conclusions. Given that we encounter scientific phenomena in our everyday surroundings, it is common for some students to harbor intuitive beliefs about scientific topics that have developed independently of formal science education. These misconceptions often come into conflict with the accurate concepts intended to be imparted in the science classroom. For instance, many students erroneously believe that heavier objects fall more quickly, a notion that contradicts the laws of gravitational acceleration. Even after being taught in secondary school, some of college students persist in maintaining these misconceptions. Syuhendri (2019) found that nearly 80% of the 73 college students who were pursuing a degree in physics education still held onto this erroneous belief. The extent of this prevailing misconception is surprising, especially given that the topic of gravitational acceleration is fundamental component of the secondary physics curriculum.

Metacognition plays a crucial role in guarding students from persistent misconceptions and steering them away from erroneous conclusions. Logically, only those individuals who possess a certain level of self-awareness are capable of explicitly identifying errors in their understanding, allowing them to engage in the process of reasoning regulation. Similarly, individuals possessing sufficient self-regulation skills can rectify these errors, leading to improvement in their knowledge. The ability to successfully detect errors has been observed to have a notable and positive correlation with academic performance in secondary school students (Zamora et al., 2018). The fact that misconceptions persist suggests that students, without actively engaging their metacognitive abilities, may not identify errors in their perceptions and consequently fail to rectify them when confronted with contradictory data during their scientific inquiry in the classroom. In other words, just presenting students with anomalous data appears insufficient for achieving the expected conceptual changes. Learning from anomalies involves metacognitive processes where students engage in recognizing and rectifying errors. This process requires us being aware of our mistakes, assessing them, and updating our knowledge to prevent repeating the same mistakes in decision-making (Fleming & Lau, 2014; Yeung & Summerfield, 2012). In this vein, the persistence of misconceptions among students engaged in scientific inquiry implies that these students lack the metacognitive abilities that are essential for effectively overcoming these conceptions.

Indeed, extensive research supports the assertion that numerous students lack the required metacognitive skills to attain meaningful learning outcomes through the process of scientific inquiry. It is reported that the majority of students do not automatically engage in metacognitive reasoning (Baird 1990; Conner 2007; Ertmer & Newby, 1996; Keselman, 2003; Kuhn & Dean, 2004; Lin, 2001). Kuhn and Dean (2004) hypothesized that proficient scientific thinking cannot be assumed to emerge ‘naturally’ without substantial educational support. Numerous researchers indicated that students experience various learning difficulties due to the lack of metacognitive skills in unsupported inquiry-based learning (Alferi et al., 2011; Arnold et al., 2014; De Jong & Van Joolingen, 1998; Kirschner et al., 2006; Klahr & Nigam, 2004). The study by De Jong and Van Joolingen (1998) may shed light on the underlying reasons for these difficulties. Their research observed that students showed deficiencies in the interpretation of data and planning and monitoring of learning in settings where inquiry-based learning was not adequately supported. In order to transition from their existing misconceptions to a scientifically accepted understanding within the frame of scientific inquiry, students must be guided to engage in reflection, discussion, and evaluation of their own interpretations, observations, and conclusions through more explicit interventions. Therefore, adequate metacognitive support becomes crucial for facilitating positive learning outcomes through a scientific inquiry process by enabling students to employ their metacognitive abilities throughout the course of scientific inquiry.

Case Study: Understanding Force and Motion

The subject of force and motion has been extensively studied because it is a topic where students often form misconceptions outside the formal science education, and these misconceptions can be difficult to correct. According to Newtonian mechanics, an object at rest remains at rest without the need for force, and an object in motion remains in its motion without an external force. In other words, the presence of motion does not indicate the presence of force. For example, an object in motion continues along a straight path at a constant speed unless influenced by an external force. While grasping Newton’s universal laws of motion as a theory might seem straightforward, achieving a complete understanding of the concepts of force and motion in perfect alignment with these laws can be challenging. This difficulty stems from the observations made in our daily lives, where we notice that objects gradually decelerate or eventually come to a stop after being set in motion by an external force. Of course, objects behave in this way because of an external force, namely friction or air resistance. Some individuals, however, mistakenly believe that objects will naturally decelerate (i.e., in the absence of an external force) or come to a stop unless some force continues to act upon them. Similarly, others hold the misconception that these laws only apply in idealized scenarios, such as situations with zero friction, and do not have universal validity throughout the entire universe, including Earth.

This widespread misperception has given rise to an explanatory framework based on the concept of “impetus”. In this framework, objects initiated into motion are thought to acquire an impetus or internal force while in motion. Over time, this impetus gradually diminishes and weakens, resulting in the slowing down and eventual cessation of the object’s movement (Clement, 1982; McCloskey, 1983; McCloseky et al., 1980). It is crucial to emphasize, however, that the slowing down and stopping of objects on Earth do not occur due to an internal force (impetus) that dissipates to facilitate motion. Instead, this phenomenon is primarily attributed to an external force, specifically friction. The presence of forces like friction acting on moving objects on Earth does not contradict Newton’s laws. Newton’s first law asserts that an object in motion will remain in motion along its path unless influenced by an external force, and the second law explains changes in velocity resulting from net forces, including friction. Nonetheless, the misinterpretation of everyday observations influenced by invisible friction, combined with an intuitive understanding of an impetus force, poses a significant obstacle to the complete assimilation of Newtonian concepts (Halloun & Hestenes, 1985).

Beliefs rooted in the impetus theory, however, contradict the wealth of sensory and motor experiences we gather through our daily interactions with the environment where friction has no role. Our bodily experiences consistently uphold the principles of Newtonian mechanics. This consistency is essential because Newton's laws of motion are expected to be universal and applicable in any circumstances throughout the universe. This suggests that by incorporating our bodily experiences into the assessment of our comprehension of force and motion, we can address and rectify our misconceptions associated with the impetus theory of force and motion.

We can utilize our physical experiences and past records as evidence to attain an accurate comprehension of force and motion. For example, we do not feel horizontal forces exerted on us because of the Earth's spinning nor do we observe any forces affecting objects nearby due to the Earth's rotation and its movement in space. As Galileo demonstrated in his thought experiment, if we were to place butterflies inside a glass jar on a boat moving steadily in a straight path, we would witness the butterflies continuing their flight independently of the boat's motion. This occurs because once they are released from the glass jar, there are no forces at play influencing their movement due to the boat's motion (Galilei, 1953). Similarly, if we find ourselves in a vehicle moving at a constant speed with devoid of visual or auditory cues, distinguishing between 50 miles per hour and 500 miles per hour would be impossible since distinct forces associated with either velocity are absent. Furthermore, we can use our mental models of the world, which are shaped by the combination of sensory input and motor experiences, as a means to address our misconceptions and establish a Newtonian understanding that motion does not indicate the presence of force. For example, when we move in the direction of the West, we do not apply additional force to counteract the Earth's West-East rotation, in the same way that we do not compensate for Earth's motion when dropping an object.

Learning from Anomalous Data

We observe abundant evidence in both our physical experiences and our perceptual-motor representations of force and motion that align with Newton's law of motion. Therefore, it becomes clear that we should recognize these conflicts with our impetus theory of motion and, as a result, acknowledge the necessity of revising our misconceptions. However, the prevalence of the impetus theory among many individuals raises the fundamental question of how it continues to persist.

A compelling explanation is that individuals who adhere to the impetus theory may not recognize errors in their observations of anomalous data that contradict their theory. Consequently, they may fail to rectify their misconceptions, leading to a lack of updating in their knowledge. As discussed in the previous paragraphs detailing how we can reconcile conflicts between the impetus theory and the Newtonian perspective, our ability to recognize these discrepancies and our endeavors to leverage our physical experiences and mental representations are crucial steps in effectively addressing and overcoming such enduring misconceptions. In other words, it is essential to possess sophisticated metacognitive abilities that empower us to detect inconsistencies in anomalous data, assess these discrepancies, and revise our understanding in order to attain accurate knowledge (Fleming & Lau, 2014; Yeung & Summerfield, 2012).

Focusing on a more specific context, this implies that students who do not possess these critical metacognitive skills may face obstacles in attaining meaningful learning outcomes in their science education, particularly within the framework of scientific inquiry. This is because scientific inquiry necessitates a sequence of metacognitive reasoning process, including the ability draw conclusions from interpreting raw data. Substantial research backs this assertion, affirming that students do encounter diverse learning challenges when metacognitive skills are lacking in a learning environment without adequate support (Alferi et al., 2011; Arnold et al., 2014; De Jong & Van Joolingen, 1998; Kirschner et al., 2006; Klahr & Nigam, 2004). These findings can be complemented by additional research that indicate that most students do not naturally initiate metacognitive reasoning processes, underscoring the importance of guidance for students to engage in self-reflection, discussions, and evaluations of their own comprehension, observations, and conclusions (Champagne et al., 1982; Weaver, 1998). This raises fundamental questions: how can we provide the necessary support to enhance students' metacognitive reasoning and facilitate improved learning outcomes, especially within the context of scientific inquiry, particularly when dealing with anomalous data?

In a recent study by Bascandziev (2023), the primary objective was to investigate how individuals recognize and correct errors in their understanding, particularly in the context of force and motion. The study involved 1149 adult participants engaging in thought experiments where they predicted outcomes and explained their reasoning in scenarios related to object motion. Two experiments were conducted: Experiment 1 had participants reason about forces acting on their bodies during motion, while Experiment 2 had them consider forces' effect on external objects in similar contexts. Both experiments had three conditions: (i) baseline condition, which presented thought experiments without specific prompts to evaluate spontaneous belief revision; (ii) comparison condition, which prompted participants to compare pre-training and training thought experiments; and (iii) argument condition, where participants were presented with a logical argument that challenges impetus beliefs, allowing researchers to assess its impact on belief revision compared to the baseline condition. This study reveals that participants in the comparison and argument conditions, where they received metacognitive prompts or logical inferences, were the only ones who revised their beliefs between the pre- and post-training phases. In contrast, those in the baseline condition, devoid of metacognitive cues, did not alter their misconceptions. This underscores the critical role of metacognition in recognizing and rectifying errors in our explanatory understanding, especially in the context of learning. As the ability to detect and evaluate arguments is fundamental to the effective scientific inquiry, the effectiveness of the scientific method relies on individual learners' utilization of proper metacognitive processes.

Metacognitive Support for Secondary School Students

Bascandziev's study (2023) highlights the effectiveness of metacognitive support in aiding learning through error detection. However, a notable limitation arises when contemplating its applicability to secondary school students. It is reasonable to assume that metacognitive interventions, which relate to relational and argumentative reasoning, are feasible only if we can assume that secondary school students possess a similar level of metacognitive abilities necessary for engagement in this type of training. Although there is no definitive biological timeline that governs an individual's metacognitive development, it is widely acknowledged that age significantly influences a student's learning approach and engagement in metacognitive activities.

Additionally, the younger population should exhibit a comparable degree of openness and flexibility, similar to that observed in adults, in order to abandon their misconceptions in favor of embracing a new knowledge that might appear contradictory at first. Adolescents are often characterized as undergoing a phase of intense sense of skepticism. They have a tendency to view objective facts as subjective opinions, considering them as person possessions immune to questioning or challenge by others (Kuhn & Dean, 2004).

Indeed, such age-related impacts are pronounced in classroom settings. According to a study examining the impact of metacognitive support (Brod, 2021), lower secondary school students demonstrated diverse learning outcomes depending on the type of metacognitive support they received. For instance, after being trained to answer test questions, these students displayed positive learning outcomes. However, their learning outcomes were more varied when they were trained on generating questions. Brod (2021) suggests that the reason for the mixed learning outcomes could be attributed to the participants' lack of mature metacognitive abilities. In other words, the impact of a metacognitive intervention depends on the learner's individual metacognitive abilities.

Moreover, it is essential to consider various individual differences within the younger learner's group when assessing the effectiveness of metacognitive support in science learning. Each student possesses varying degrees of metacognitive abilities, influencing how, when, and which strategies they employ when learning through scientific inquiry. For instance, some students face significant challenges in error detection with external assistance, and this difficulty persists even when provided with more direct support (Zamora et al., 2016). Additionally, this study revealed a noteworthy positive correlation between students' proficiency in error detection and their overall performance in both subject matter and tests. This highlights the crucial role of a student's individual competence in subject knowledge in the learning process. High-achieving students, for instance, are more likely to leverage their subject knowledge when making judgements to identify errors. Therefore, it is imperative to explore how these individual differences in metacognitive abilities impact the effectiveness of metacognitive support in learning through scientific inquiry.

In summary, these findings underscore the importance of investigating two key aspects to assess the effectiveness of metacognitive support in improving learning outcomes through scientific inquiry among secondary school students: (i) how secondary school students employ metacognitive prompts during the process of scientific inquiry, and (ii) how individual differences are correlated to the learning process among younger learners through metacognitive support.

Present Study

The process of scientific inquiry, especially when prompted by conflicts encountered during discovery, remains an integral and valuable component to teaching and learning science in secondary school education. As students engage in scientific inquiry, they inevitably confront conflicts in observed phenomenon that contradict their existing beliefs. To integrate this cognitive dissonance into their knowledge framework, students must effectively leverage their metacognitive abilities to identify and correct errors in their misconceptions. However, as evidenced by a corpus of literature, merely exposing students to conflicting representations appears to be insufficient in eliciting the anticipated conceptual changes. To facilitate successful learning, a metacognitive intervention is necessary to aid students in discovering and evaluating the dissonance between their existing knowledge and new information, ultimately leading to the successful construction of new knowledge.

This present study serves as a follow-up to Bascandziev's research (2023), employing a similar experimental design but tailored for secondary school students. The primary objective is to investigate whether adolescents, as opposed to adults, can exhibit improvement based on thought experiments that evoke conflicting representations, both with and without the inclusion of metacognitive prompts. Additionally, the study aims to explore the potential correlation between their individual metacognitive reasons abilities and their learning outcome. With this objective in mind, this study endeavors to address the following research questions:

i. How would adolescents, some of whom are taking physics concurrently, perform on the pre-training thought experiments?

ii. Are adolescents' metacognitive abilities related to how they perform on questions about force and motion? Are adolescents' metacognitive abilities predictive of the ability to revise beliefs in the face of elicited conflicting representations?

iii. Is there a potential disparity among adolescents in comprehending force and motion, specifically in the context of the impetus theory and the accurate understanding based on Newtonian mechanics, when presented through various representations about force and motion?

iv. Would adolescents engage in belief revision processes if inconsistent beliefs are elicited with the help of thought experiments, and would metacognitive prompts enhance such belief revision processes?

This study recruits secondary school students aged 12 to 17 and employs an experimental design with both a control group and an experimental group. The study comprises three stages of training: pre-training, bodily training, and post-training. In the pre-training phase, participants are tasked with making predictions regarding four questions related to object trajectories in scenarios involving force and motion. During the bodily training phase, they are asked to make predictions about another set of four items that are designed to deliberately elicit an accurate response consistent with Newtonian mechanics. To succeed in this task, they need to utilize their personal bodily experiences within specific scenarios, which differs from their approach in the pre-training phase, where they make predictions from the viewpoint of an independent object. In the post-training stage, participants revisit the same four items presented in the pre-training phase.

The key distinction between the two group lies in the presence of metacognitive prompts. Specifically, the experimental group receives two types of prompts between the bodily and post-training sessions, whereas the control group receives none. The first prompt is administered after each of the four bodily training items. Its purpose is to assist students in drawing comparisons between the questions in the pre-training and bodily training questions. The second prompt is introduced during the post-training phase, appearing before each question. This metacognitive cue encourages participants to reconsider their initial responses provided during the pre-training phase. Its design is aimed at prompting participants to reevaluate their initial decisions due to the identical nature of the items in both the pre-training and post-training phases.

In addressing the research question regarding participants' use of metacognitive abilities in thought experiments and their potential correlation with learning outcomes, this study employs the Junior Metacognitive Assessment Inventory, which includes a self-report scale rooted in a two-factor model based on the Brown framework of metacognition.

The Junior Metacognitive Awareness Inventory (Jr. MAI) is one of the few self-assessment tools tailored for evaluating metacognition in children from grades 3 to 9 (Sperling et al., 2002). It is a version developed specifically for children based on the 52-item Metacognitive Awareness Inventory, which was originally created by Schraw and Dennison in 1994 and is widely used as a self-report measure of metacognition in adults (Ning, 2019). This study utilizes Version B of the Jr. MAI, designed for students ranging from grade 6 to 9.

The selection of the Jr. MAI for this study is justified by its compatibility with the online survey format employed in this study. Furthermore, the main goal of this study corresponds with the main purpose of the Jr. MAI, which seeks to identify learners who could benefit from metacognitive interventions and to serve as an evaluation tool to assess the impact of ongoing interventions. In this study, the Jr. MAI was administered following the implementation of the post-training to both a control group and an experimental group~~.~~

The Version B of the Jr. MAI comprises two distinct domains of metacognition: knowledge of cognition and regulation of cognition. Knowledge of cognition is a crucial factor in evaluating the effectiveness of metacognition (Krathwohl, 2002). It also encompasses insights into the ‘what’, ‘how’, ‘when’, and ‘why’ aspects of cognitive processes (Ping et al., 2015). It comprises three dimensions of cognitive awareness: declarative knowledge, procedural knowledge, and conditional knowledge (Schraw & Dennison, 1994). Declarative knowledge encompasses information about a subject (Azevedo & Aleven, 2013) and an individual’s comprehension of their existing knowledge, learning strategies, and the factors influencing the learning process (Young & Fry, 2012). Procedural knowledge refers to understanding effective techniques for achieving specific learning goals and being aware of how particular cognitive skills are employed during the learning process (De Backer et al., 2012). Conditional knowledge pertains to the recognition of external conditions that justify the appropriate use of effective strategies (De Backer et al., 2011). It involves understanding when and how to apply prior knowledge, such as deploying various strategies depending on specific circumstances (Larkin, 2010).

The second domain in the Jr. MAI is regulation of cognition, which is further divided into four components in Version B: planning, monitoring, evaluation, and information management skills. Regulation of cognition involves an individual’s use of various self-regulation processes to control and oversee their learning (Arzt & Armour-Thomas, 1992; Baker, 1989; Schraw & Dennison, 1994; Schraw et al., 2006). These processes encompass planning (i.e., setting goals and allocating resources before learning), information management (i.e., employing strategies to structure and process information), debugging (i.e., correcting understanding and errors during learning), and evaluation (i.e., assessing one's performance and the effectiveness of strategies after learning is completed).

Chapter 2.

Method

In adopting an experimental design, the primary objective of this research is to discern casual relationships pertaining to the metacognitive interventions and their impact on performance within the cohort of secondary school students involved. Furthermore, the study aims to explore correlations among individual variables of participants, including metacognitive abilities, age, and prior knowledge, in relation to observed learning outcomes. This chapter furnishes a comprehensive exposition of the experimental framework, elucidates the criteria for selecting participants, and delineates the procedures adhered to during the data collection phase.

Participants

The participants in this study were adolescents aged between 12 and 17 years. Due to their legal status as minors, the process of enlisting participants involved a series of steps. Prior to the commencement of this study, ethical approval was secured from the Harvard University Committee on the Use of Human Subjects on February 4, 2022. The approval process involved a comprehensive review of the research design, methodology and ethical safeguards to ascertain compliance with established standards. Informed consent forms were administered to all participating adolescents and their parents. These documents comprehensively outlined the nature of the study, potential risks involved, and emphasized the voluntary nature of their participation.

Initially, the researcher extended study invitations to international schools in Korea and Malaysia that offer secondary education and express interest in involving their students in the current research. After obtaining consent, the schools informed parents of the students of this study by sharing the recruitment invitation letter via their internal email system. Some parents regarded this study as a valuable opportunity for learning and willingly disseminated the recruitment details through diverse online communities of school parents. Parental consent for their children's participation in the study was obtained, and parents provided their personal email address to facilitate the distribution of individual online survey questionnaires. Only adolescents whose parents signed a consent form participated in the study. Ninety-four parents provided their consent and email address. This sample of 94 students was randomly assigned to two groups: a control group and an experimental group. The study was conducted online. Survey questionnaires were sent individually to each participant based on their group assignment. Out of the 94 invitations, 22 students from the control group and 29 from the experimental group responded to the survey. Some participants were excluded for reasons, such as incomplete survey submissions, failure to pass control questions for inattentive responses, and inadequate explanations in their required task (e.g., entering random words or symbols). The final sample included 36 participants ($N = 36$), evenly split between the control group ($n = 18$) and the experimental group ($n = 18$), with an average age of 14.8 (range = 12 – 17; $SD = 1.62$). Among these participants, 24 were identified as females, and 12 as males. Additionally, 21 of the 36 students (58.3%) reported having taken a physics course, while 15 (41.7%) had not taken any physics courses.

Procedure

After submitting their consent, participants proceeded to engage in the thought experiments, followed by self-assessment on their metacognitive abilities using the Junior Metacognitive Awareness Inventory. Subsequent to the completion of these two tasks, participants responded to demographic questions, including age and gender, and provided self-reported information regarding their prior knowledge in physics.

Design and Stimuli

In both the control and experimental groups, each participant went through three phases: pre-training, bodily training, and post-training. Each of the three phases consisted of four thought experiments. The thought experiments prompted participants to imagine scenarios in which force and motion were the critical variables. The thought experiments in both the pre-training and post-training phases, which were identical, were designed to deliberately elicit impetus responses (misconceptions), while the thought experiments in the bodily training phase were intended to evoke Newtonian responses (accurate understanding). This design allowed for the same participants to express incorrect impetus ideas some of the time (e.g., at pre-training) and to express correct Newtonian ideas some of the time (e.g., at training), thus making the conflict between impetus and Newtonian ideas explicit.

The training sequence is structured with a specific aim: participants first express errors at pre-training, then revaluate and refine their understanding through different presentations in the bodily training, and finally, they reassess their misconceptions in the post-training phase by responding to the same items used in the pre-training. All of the tasks in this study are the same as those used in the previous study by Bascandziev

(2023), with the only difference being that the current study incorporates visual depictions of the scenarios to ensure younger participant’s better comprehension, while the adult study relied solely on textual descriptions. (For a visual presentation of the thought experiment tasks , refer to Figure 1 and 2 below.)

In the pre-and the post-training phase, participants were instructed to predict either the path the object would follow or its eventual landing point. One of such example of a thought experiment is the following “A train is moving at a constant velocity of 100 MPH in a straight line. Inside the train, there is a mechanical claw that is holding a ball. The mechanical claw is fixed and rigid and so it does NOT move as a result of vibrations. Furthermore, the claw is located halfway along the ceiling between the front and the rear ends of the car. At one point, the ball is released. Please ignore air resistance. There is no wind inside the car. The ball will fall: a) Behind the halfway point of the car floor; b) Exactly on the halfway point of the car floor.”

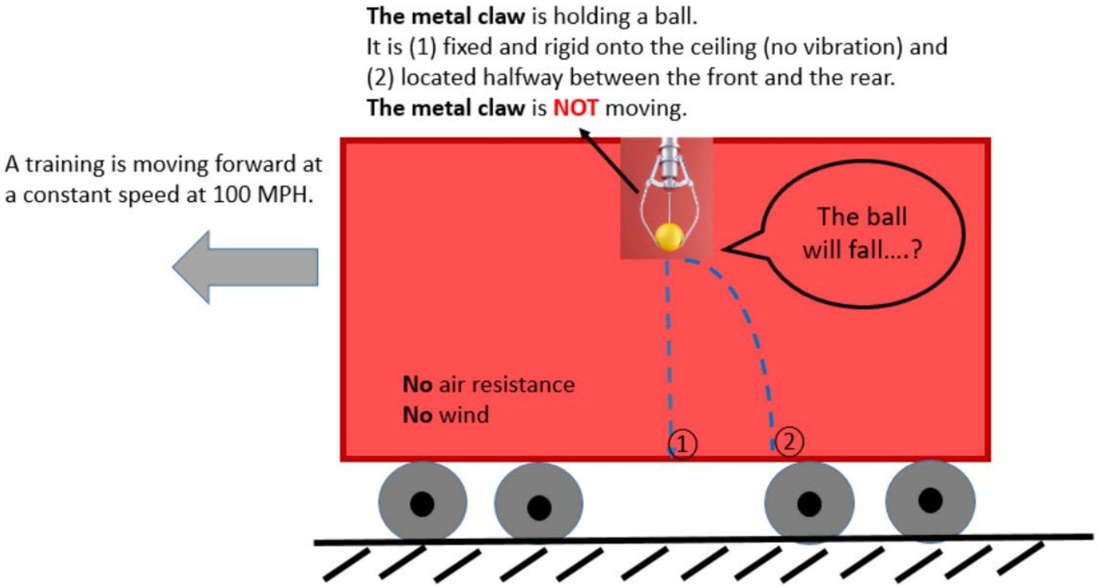
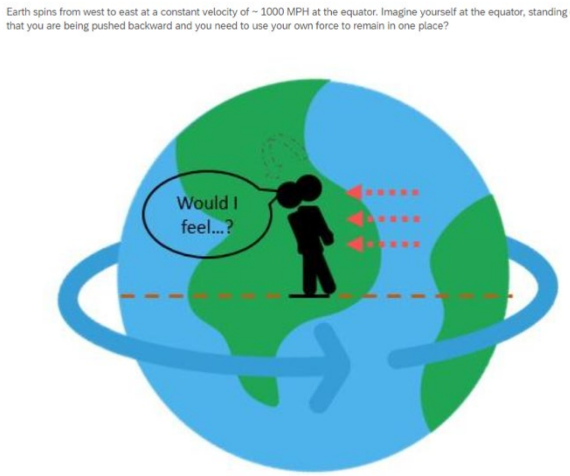


Figure 1. Pre-Training Thought Experiment Exemplar

Participants were tasked to predict the landing point of a moving object across four specified scenarios.

A typical incorrect answer, aligning with the impetus theory of motion, asserts that the ball would fall behind the midpoint of the car's floor because once separated from the claw, it will progressively lose the impetus imparted by the train and decelerate relative to the train's motion. Following the completion of each task, participants detailed the foundation of their answer (e.g., theoretical knowledge, person experience, simulation, or not sure). Participants were free to select multiple options as the underpinning for their response. Then participants were prompted to evaluate their confidence level in the rationale behind their answer. Finally, participants were asked to provide a rationale for their response exclusively after engaging in the pre-training and the post-training thought experiments.

In the bodily training phase, participants engaged in four bodily tasks where they assessed their bodily experience in specific scenarios. One example is “Earth spins from west to east a constant velocity of ~ 1000 MPH at the equator. Imagine yourself at the equator, standing on a flat surface, facing east. Would you feel that you are being pushed backward and you need to use your own force to remain in one place? a) Yes, I would feel forces pushing my body in a direction opposite from the direction in which the earth is moving, b) No, I would not feel any forces pushing my body in a direction opposite from the direction in which the earth is moving.” Participants were tasked to make prediction by utilizing their personal bodily experience across four specified scenarios. The accurate response on this particular thought experiment is that the individual would perceive no sensations of pushing or pulling on their body, aligning with the Newtonian law that bodies at rest remain at rest without introducing external forces.



Earth spins from west to east at a constant velocity of ~ 1000 MPH at the equator. Imagine yourself at the equator, standing on a flat surface, facing east. Would you feel that you are being pushed backward and you need to use your own force to remain in one place?

Figure 2. Bodily Training Thought Experiments Exemplar

Participants were tasked to make prediction by utilizing their personal bodily experience across four specified scenarios.

Only the experimental group underwent distinct metacognitive interventions immediately following the pre-training and during the bodily training phase. The first intervention entailed providing participants a question, prompting them to engage in metacognitive reasoning between the pre-training tasks and the subsequent bodily training tasks scheduled to commence: "Next, you will see several questions. They are designed to improve your understanding of the questions you answered a minute ago. As you go through the new questions, think hard about how the answers to the new questions related to the answers you gave a minute ago." If you read this carefully, please choose the option "2" below. The second intervention involves instructing participants to draw comparisons between the thought experiment tasks conducted during the pre-training phase and those undertaken in the bodily training phase. The comparison prompt was administered following each task throughout the entirety of the bodily training phase. The prompt asks "Do you think that the answer you gave on this last question is related to the first set of questions that you received at the beginning of the study? For example, do you think the last question is similar to the questions about where the ball would fall in a train car traveling at a constant velocity?" a) Yes, b) No."

Following the conclusion of the thought experiments, participants were requested to assess their metacognitive learning behaviors using the Junior Metacognitive Awareness Inventory (Jr. MAI). The instrument has undergone a rigorous evaluation as a reliable measurement tool for assessing adolescents' metacognitive awareness. This assessment, supported by precision, is substantiated through a recent statistical analysis conducted with a sample of students from Singapore (Ning, 2018). Jr.MAI Version B, tailored specifically for students in grades 6 to 9, consists of 18 questions organized into two primary domains: nine questions pertain to knowledge of cognition, while the remaining nine focus on the regulation of cognition. The domain of knowledge of cognition is further subcategorized into conditional knowledge, declarative knowledge, and procedural knowledge. In contrast, the domain of regulation of cognition includes subcategories such as planning, information management skills, monitoring, and evaluation (refer to Appendix 2 for the complete set of items in Jr.MAI Version B). Participants provided self-ratings for each item on a Linkert 5 scale, ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). An exemplar question representing procedural knowledge within the domain of knowledge of cognition is “I try to use strategies that have worked in the past.” An example question representing information management skills within the domain of regulation of cognition is “I draw pictures or diagrams to help me understand while learning.”

Chapter 3.

Results

This chapter presents the study's outcomes and findings. The principal objective was to examine participants' performance across training phases, assess the impact of the metacognitive intervention, and explore potential correlations between individual variables and performance using a combination of descriptive and inferential statistics. The results emanate from an investigate process guided by the theoretical framework outlined in Chapter 2. The following sections provide a systematic overview of significant findings, categorized according to themes derived from data analysis. Each thematic exploration is intricately tied to the research questions, facilitating a nuanced understanding of the observed phenomena.

Pre-training Performance (Descriptive Statistics)

Participants ($N = 36$) in both control and experimental groups showed an average performance of 2.42 on a 4-point scale, with a standard deviation of 1.40. The performance was calculated based on the total correct responses made by participants across four items during the pre-training phase. Segmented by group, the control group exhibited a mean score of 2.39, with standard deviation of 1.42. In parallel, the experimental group demonstrated a mean score of 2.44, with a standard deviation of 1.42. Examining individual tasks: the percentage of participants in both groups who answered each of the four pertaining tasks correctly was as follows: Task 1 = 66.7%, Task 2 =

72.2%, Task 3 = 52.8%, and Task 4 = 50%. This level of performance aligns with the results reported in Bascandziev's study (2023) and is consistent with findings from previous studies. Those studies demonstrated that participants provided correct Newtonian responses ranging from 47% to 68%, depending on the specific problem questions (McCloskey et al., 1980).

Participants in both groups were tasked with composing sentences elaborating their justifications for their responses to the first task in the pre-training phase. These explanations were subsequently categorized into four distinct groups: (i) impetus-based justification, (ii) Newtonian-based justification; (iii) personal experience-based justifications; and (iv) miscellaneous responses, encompassing guesses, irrelevant statements, or an absence of justifications.

To qualify as an impetus-based justification, the reasoning needed to incorporate the concept that the ball's movement is contingent upon its connection to the train, and that when this connection is severed, the ball's forward motion will gradually decrease in speed relative to the train. For instance, participants provided the following examples of such justifications: a) "Because the train is moving during the time the ball falls" and b) "The train is still moving, but the ball will remain stationary in the air when it is released." To qualify as a Newtonian justification, the reasoning needed to encompass the notion that both the train and the ball are moving at the same velocity, belong to the same frame of reference, or remain unaffected by external forces influencing the ball's speed. Examples of such justifications include: a) "Because the speed of the train is not affecting the ball, therefore no forces are acting on the ball except for gravitational potential energy" and b) "The ball will continue to have the same horizontal velocity as the car because there is no other force acting upon the horizontal axis." To qualify as a Personal experience-based justification, the reasoning needed to draw upon personal experience as a foundation for judgment. Examples of such justifications are: a) "I have seen this experiment before" and b) "The earth rotates on its axis, but when we drop something, it falls in a straight line." Finally, some participants either did not provide any justifications or offered irrelevant justifications, such as "Due to momentum of the train and the inertia." In participants offering accurate responses (*n*= 24), the majority (83.3%) provided Newtonian-based justifications, whereas a smaller portion (16.7%) utilized personal experiences as the basis for their explanations. In contrast, among participants with incorrect responses (*n*= 12), a significant majority (83.3%) employed impetus-based justifications to substantiate their responses, while the remaining few offered irrelevant rationales, such as referencing momentum.

This outcome closely mirrors the results obtained from a similar experiment conducted with the adult population (Bascandziev, 2023). In that experiment, an overwhelming majority of participants who utilized Newtonian justifications (98.6%, *n* = 214 out of 217 participants) arrived at correct answers. Simultaneously, among the 169 participants who employed impetus-based justifications, only a small fraction (4.1%) exhibited accurate assessments on the pre-training tasks.

After articulating their justifications for responses, participants proceeded to self-rate their confidence levels, indicating the extent of assurance in their answers on a scale ranging from 1 (Not at all confident) to 5 (Very confident). The overall mean confidence level among the participants (*N* = 36) was 3.22, accompanied by a standard deviation of

0.91. Specifically, the control group (*n* = 18) exhibited a mean of 3.24 (*SD* = 0.79), and the experimental group (*n* = 18) displayed a mean of 3.19 with an *SD* of 1.04.

Bodily Training Performance (Descriptive Statistics)

Participants in both groups (*N* = 36) achieved a grand mean of 3.28 on a 4-point scale with a standard deviation of 0.78 in terms of correct responses. Broken down by each group, the control group exhibited a mean score of 3.39 with a standard deviation of 0.85, while the experimental group showed a mean score of 3.17 with a standard deviation of 0.71. Segmented by individual bodily training tasks, the percentage of participants in both groups (*N* = 36) who answered correctly were as follows: Task 1 = 52.78%, Task 2 = 83.33%, Task 3 = 94.44%, and Test 4 = 97.22%. The observed outcomes indicated superior overall performance when contrasted with the adult population in a previous study, where Task 1 = 64%, Task 2 = 66%, Task 3 = 73%, and Task 4 = 75% (Bascandziev, 2023).

Following the articulation of their response justifications, participants (*N* = 36) engaged in self-assessment of their confidence levels regarding the bodily training tasks on a scale ranging from 1 (Not at all confident) to 5 (Very confident), yielding a grand mean of 3.69 with a standard deviation of 0.88. Broken down by each group, the control group exhibited a mean score of 3.79 with a standard deviation of 0.81, while the experimental group showed a mean score of 3.58 with a standard deviation of 0.96.

Impact of Age, Prior Knowledge, and Metacognitive Abilities on Performance

This section presents the outcomes of an investigation exploring potential correlations between participants' pre-training performance and a range of relevant variables. The variables of interest were measured through demographic surveys encompassing factors such as age, metacognitive abilities, and prior experience with physics courses. (Refer to Table 1 for specific correlation coefficients for each variable). Notably, none of the observed correlations in this analysis achieved statistical significance.

Table 1. Descriptive Statistics and Correlations for Individual Variables

Variable	*N*	*M*	*SD*	1	2	3	4
1. Age	36	14.8	1.6	—			
2. Physics Course [a]	36	0.6	0.5	0.023	—		
3. Pre-Training Performance [b]	36	2.4	1.4	-0.058	-0.194	—	
4. Metacognition [c]	36	54.2	13.0	0.166	0.24	0.194	—

[a] *Physics course Experience: A binary variable representing participants' prior exposure to physics courses in school. A value of "0" signifies the absence of prior physics course experience, while "1" signifies the presence of such experience.*

[b] *Pre-training Performance: Refers to the cumulative count of correct responses achieved by participants during the pre-training phase, with a possible score range from 0 to 4.*

[c] *Metacognition Score: Represents the total score derived from the 18 items of the Jr.MAI (Junior Metacognitive Awareness Inventory). Participants provided self-ratings for each item using a 5-point Likert scale, ranging from 1 (Never) to 5 (Always).*

Between Group Difference in Bodily Training Performance

The primary objective of this study was to examine the impact of metacognitive interventions on performance, exclusively administered to the experimental group. As a first step, I investigated whether the metacognitive prompts given to the experimental group influenced the participants' performance on the training (bodily) thought experiments, as well as on their confidence on those thought experiments. An independent-sample t-test was conducted to assess mean differences between the groups. The results revealed a non-significant difference ($t(34) = 0.85$, $p = .40$), with a mean score of 3.17 ($SD = 0.71$) in the experimental group ($n = 18$) and a mean score of 3.39 ($SD = 0.85$) in the control group ($n = 18$) in the bodily training tasks. Furthermore, there was no significant difference between the groups in confidence levels ($t(34) = 0.70$, $p = .49$), as evidenced by the mean score of 3.58 ($SD = 0.96$) in the experimental group ($n = 18$), and the mean score of 3.80 ($SD = 0.81$) in the control group ($n = 18$).

Performance Difference Between Pre-training and Bodily Training

The study utilized thought experiments to explore participants' comprehension of the concept of force and motion across various presentations in both pre-training and bodily training tasks. (See Appendix 1 for the complete set of thought experiments employed in the pre-training and bodily training). The examination of mean performance differences between the two phases revealed that both groups produced more accurate responses during the bodily training tasks in comparison to the pre-training tasks. Specifically, during the pre-training phase, participants in both groups ($N = 36$) scored a grand mean of 2.42 on a 4-point scale with standard deviation of 1.40. In contrast, during the bodily training phase, both groups ($N = 36$) exhibited a grand mean of 3.28 with standard deviation of 0.78. (Refer to Figure 3 for an illustration of the performance difference between the pre-training and bodily training phases).

The hypothesis suggested that providing the experimental group with a metacognitive prompt immediately after pre-training, encouraging greater engagement in metacognitive reasoning would result in statistically significant improvements in bodily training performance. This would be in contrast to the control group, which did not receive any prompts. A two-factor repeated measures ANOVA was employed to determine whether the experimental group exhibited a significantly distinct improvement in performance during the bodily training phases compared to the control group. The analysis encompassed two factors: the training phases and the group. The result indicated that the training phase had a statistically significant effect on performance, with a substantial effect size ($F = 13.83$, $p < .001$, $\eta^2 = 0.29$). Additionally, the interaction between the training phase and group performance was found to be non-significant ($F = 0.36$, $p = .55$, $\eta^2 = 0.01$), as well as the between-group effect ($F = 0.08$, $p = .79$, $\eta^2 = 0.02$, indicating that the observed improvement did not differ significantly between the two groups across the pre-training and bodily training phases.

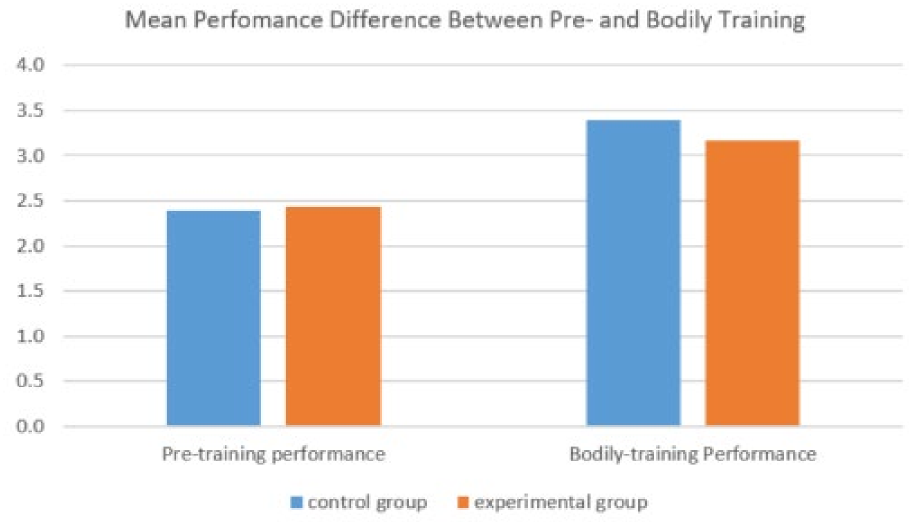


Figure 3. Mean Performance Difference Between Pre- and Bodily Training

The figure illustrates the improvement in the number of correct responses between the pre-training and bodily training phases for both the control and experimental groups. The performance refers to the cumulative count of correct responses achieved by participants during both phases with a possible score range from 0 to 4.

To assess whether the observed performance improvements in both groups were reflected in participants' confidence regarding their responses during both the pre-training and bodily training phases, mean scores of confidence levels in each group were compared between the pre-training and bodily training. The control group (n = 18) achieved a mean score of 3.24 (SD = 0.79) in the pre-training tasks, while the experimental group (n = 18) attained a mean score of 3.19 (SD = 1.04). Their confidence levels in the bodily training tasks were mean score of 3.80 (SD = 0.81) for the control group and mean score of 3.58 (SD = 0.96) for the experimental group. The repeated measures ANOVA analysis established that the disparities in confidence levels between the two training phases were statistically significant, denoted $F = 8.67$, $p < .01$, $\eta^2 = 0.20$.

However, the group difference and the interaction between the training phases and confidence levels revealed a non-significant difference: *F* = 0.24, *p* = .63, η^2 = 0.007 and *F* = 0.27, *p* = .61, η^2 = 0.008, respectively.

Performance Difference Between Pre-training and Post-training

They study hypothesized that the metacognitive prompt, administered to the experimental group during the bodily training phase, would enhance performance in post-training tasks. Specifically, participants were prompted to assess whether they could identify a logical comparison between the pre-training tasks and the bodily training tasks. To test the hypothesis, an initial analysis of the mean performance difference between the pre-training and post-training phases was conducted. Both control and the experimental group exhibited minimal changes in performance between the pre-training and post-training phases. Each group, consisting of 36 participants in total, achieved mean scores of 2.42 on a 4-point (*SD* = 1.40) in the pre-training phase and mean scores of 2.42 (*SD* = 1.61) in the post training. Examining the groups separately, the experimental group exhibited a performance improvement from pre-training (*M* = 2.44, *SD* = 1.42) to post-training tasks (*M* = 2.61, *SD* = 1.58). In contrast, the control group displayed a performance decline from pre-training (*M* = 2.39, *SD* = 1.42) to post-training tasks (*M* = 2.22, *SD* = 1.67). (Refer to Figure 4 for an illustration of the performance difference between the pre-training and post-training phases). Some individuals did modify their responses, either changing from incorrect to correct or vice versa. Notably, a subset of participants who shifted their responses from correct to incorrect during the post-training phase justified this change by invoking the impetus theory.

However, it is crucial to emphasize that the impact of metacognitive interventions did not yield a statistically significant group performance difference between the pre-training and post-training tasks. A two-factor repeated measures ANOVA was performed to examine differences between the two training phases and between groups. The results revealed no significant differences in performance between the control and experiment groups ($F = 0.00$, $p = 1.00$, $\eta^2 = 0.00$). Similarly, no significant interaction was observed between group and the training phase ($F = 0.36$, $p = .55$, $\eta^2 = 0.10$).

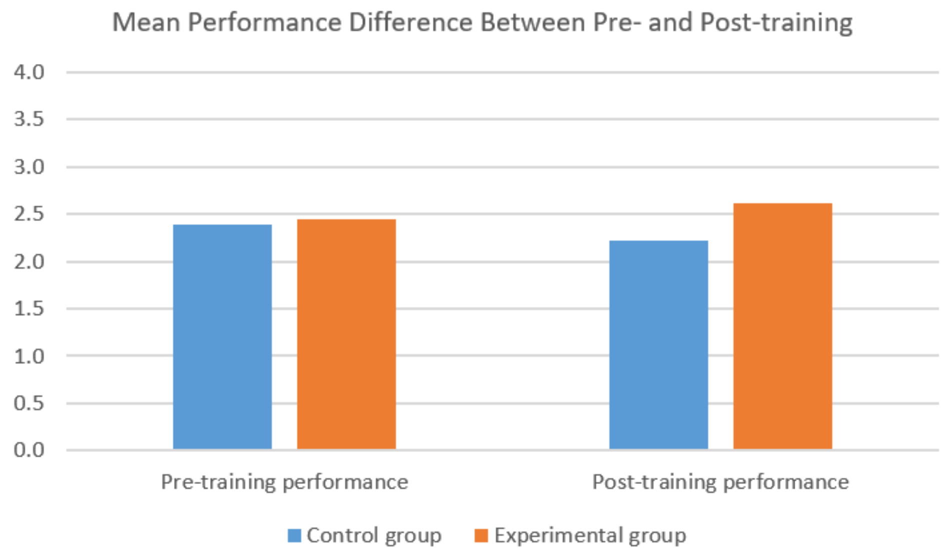


Figure 4. Mean Performance Difference Between Pre-and Post-Training

The figure illustrates a minimal difference in the number of correct responses between the pre-training and bodily training phases for both the control and experimental groups. The performance refers to the cumulative count of correct responses achieved by participants during both phases with a possible score range from 0 to 4.

Despite the minimal performance difference between the training phases, a significant difference manifested in the variation of confidence levels across the training phases. Participants in both control and the experimental group ($N = 36$) exhibited an increased confidence level in the post training, with a grand mean of 3.46 ($SD = 0.89$), compared to the pre-training phase where the grand mean was 3.22 ($SD = 0.91$). A repeated measures ANOVA analysis validated the statistical significance of the difference between the training phases, yielding $F= 4.24$, $p < .05$, $\eta^2 = 0.11$. However, the interaction between the training phases and group was found non-significant ($F = 1.0$, $p = .32$, $\eta^2 = 0.29$).

Chapter 4. Discussion

Emphasizing rigorous metacognitive abilities is paramount for successful scientific inquiry. This significance is particularly pronounced in learning challenging science topics, such as Newton's force and motion, where prevalent misconceptions often clash with accurate concepts intended for the classroom education. Metacognition, specifically the ability to detect and rectify errors in the scientific inquiry process, plays a crucial role in guarding students against persistent misconceptions and guiding them away from erroneous conclusions. However, the existing body of literature consistently indicates a deficiency in students' metacognitive abilities, resulting in learning difficulties, especially in educational settings that do not provide sufficient support (Baird, 1990; Conner, 2007; Ertmer & Newby, 1996; Keselman, 2003; Kuhn & Dean, 2004; Lin, 2001). Furthermore, recent research indicates that several factors may impact learning outcomes in science education. Specifically, there is evidence suggesting that young learners require unique forms of metacognitive support, different from what may be effective in adult populations (Brod, 2021). Additionally, secondary school students exhibit individual variations in learning outcomes following metacognitive support provided to the entire class. Despite the crucial role of metacognition in its application in science education, there is a scarcity of research addressing this area. This research gap is pronounced in the secondary school population, which has been relatively underexplored. In the current research, an experiment was undertaken to delve into the comprehension of force and motion among secondary school students. Specifically, the study aimed to evaluate the efficacy of metacognitive intervention in aiding students to identify and rectify conflicts encountered during the experiments. The experiment's data can be summarized into key findings as follows. A significant portion of adolescent participants exhibited misconceptions when predicting force and motion in scenarios involving objects, reaching a level comparable to findings in previous studies with adults (Bascandziev, 2023). The enrollment in physics courses showed no correlation with their performance at pre-training and, similarly, exhibited no correlation with their metacognitive abilities as self-assessed through the Junior Metacognitive Awareness Inventory. However, their predictions were more accurate when the scenarios incorporated bodily experiences. Despite an initial improvement in performance after bodily training, there was an absence of significant and meaningful learning outcomes during the post-training reassessment of the same tasks, with or without metacognitive intervention. In other words, engaging in the bodily training did not result in pre-to-post training improvement in either the control or experimental group. These results contradict the initially posited hypotheses and theoretical assumptions that underlie them. This necessitates a comprehensive discussion of the gathered data, shedding light on adolescents' understanding of force and motion, their strategies for resolving comprehension conflicts, the efficacy of implemented metacognitive interventions, and ways to enhance metacognitive support.

Participants' Conceptual Understanding of Force and Motion

Within the pre-training phase, a significant proportion of participants demonstrated misconceptions consistent with the impetus theory regarding the fundamental concepts of force and motion. This manifestation became apparent when participants were assigned the task of predicting the falling trajectory of an independent object released from the ceiling of a vehicle in motion. Participants articulated their conceptual understanding more clearly when elaborating on their justifications for their answers in the pre-training task. The majority (83.3%) of those providing accurate responses grounded their judgements in Newtonian principles. Conversely, a significant majority (83.3%) of participants with incorrect responses utilized impetus-based justifications. This outcome closely parallels the findings in the adult population (Bascandziev, 2023), where 98.6% of participants with correct answers employed Newtonian justifications, while only a small fraction (4.1%) of those employing impetus-based justifications demonstrated accurate responses. The results of the study support the theoretical postulation, indicating a widespread prevalence of misconception regarding force and motion. Examining the rationales provided by participants with the misconception reveals a notable connection to the impetus theory. It indicates that, when tasked with predicting the trajectory of a falling object, participants primarily drew upon their daily observations of objects, as opposed to leveraging knowledge gained from physics education. Alternatively, this trend could be linked to the majority of young participants lacking formal physics education, making them heavily dependent on personal observations for prediction tasks. This is substantiated by the data, with only 58% of participants reporting exposure to physics courses. Nevertheless, this explanation seems improbable, as adult participants with high school education also exhibited comparable performance in identical prediction tasks (Bascandziev, 2023).

Participants' Conceptual Fragmentations Across Representations

Participants exhibited notably enhanced performance in tasks involving bodily experiences, even though these tasks mirrored those in the pre-training, albeit presented through different representations from a first-person perspective. Moreover, participants reported significantly higher confidence levels when making predictions based on personal experiences compared to predictions based on observation of separate objects in the pre-training. These findings imply that participants concurrently uphold two distinct theories (i.e. the impetus theory and the Newtonian mechanics) within the overarching concept of force and motion, seamlessly transitioning between them based on the representations they encounter. A parallel phenomenon of possessing conflicting understanding about a single concept was similarly observed in both adult and children populations. Specifically, children were observed to agree with statements regarding daily encountered examples, even when they were mutually incompatible (Clark, 2006; Schneider & Hardy, 2013). These findings prompt us to question how individuals reconcile the coexistence of misconception and accurate understanding about force and motion. Did participants effectively recognize these conflicts and rectify them when asked to reassess tasks they had previously completed during pre-training? Did the metacognitive intervention contribute to improved responses, resulting in significantly better performance in the experimental group compared to the control group?

Metacognitive Resolution of Conflicting Concepts

Participants in both the control and experimental groups did not exhibit improvement in the post-training phase immediately following bodily training, despite displaying a predominantly correct understanding of force and motion. Moreover, the data did not align with the hypothesis that participants would demonstrate enhanced performance when assisted with metacognitive interventions aimed at eliciting logical connections between bodily and post-training tasks. What hindered participants from resolving conflicts in their comprehension?

The data reveal three distinct groups characterized by distinct patterns of conceptual change. The first group comprising the majority of participants, who showed misconceptions in the pre-training phase, failed to detect errors and consequently adhered to their incorrect responses. The inability to detect errors was evident in the substantial number of responses that exhibited a lack of comparison between the pre-training and bodily training tasks. The second group acknowledged the error and rectified their misbelief in the post-training. The third group initially demonstrated correct understanding in pre-training, failed to notice the error, and subsequently changed their correct answer to an incorrect one. The observed patterns in participants' conceptual changes underscore the significance of metacognitive abilities in successfully resolving their conflicting theories about force and motion. That is, even though they make up a small portion of the participants, those who successfully identified comparisons between the two representations arrived at the correct responses in the post-training phase. However, it is crucial to note that no statistically significant difference was observed between the control and experimental groups in their post-training performance. This implies that participants who received prompts designed to encourage metacognitive reasoning did not outperform the performance of the control group, which did not receive such prompts. While several explanations could account for this, the present study explored individual differences as a promising factor influencing conceptual change.

Individual Variables and Their Impact on Conceptual Change

The hypothesis suggesting a correlation between individual variables – such as age, prior knowledge, and metacognitive abilities – and a correct understanding of force and motion is refuted by the correlation analysis of the sample. However, it is worth noting that participants displayed a broad spectrum of variations in their application of metacognitive strategies in the process of problem solving, particularly in the number of judgement bases employed to answer prediction tasks across the training phases. Some students utilized zero bases, opting for ‘I am not sure’ to justify each response, while others employed up to 12 bases, incorporating theoretical knowledge, mental simulations, and personal experiences. Nevertheless, these variations did not yield significant correlations with their performance. Overall, there was minimal correlation found between performance and metacognitive abilities, while a negative correlation emerged with participant age, as well as physics course experience.

Admittedly, the absence of correlations with individual variables might be attributed to low statistical power due to a small sample size ($N = 36$). Alternatively, one could interpret this as an indication that adolescents may not have reached the developmental stage of mature metacognition. This potential disparity could impede their effective utilization of thought experiment tasks, particularly in the context of bodily training, where they evidently demonstrate superior performance compared to pre-training tasks. The identified lack of metacognitive abilities among adolescents, which is distinct from that of adult populations, is consistently documented in prior research (Baird, 1990; Broad, 2021; Conner, 2007; Ertmer & Newby, 1996; Keselman, 2003; Kuhn & Dean, 2004; Lin, 2001).

An additional constraint in interpreting the data is the sole reliance on participants' self-assessment for individual variables. For instance, a noteworthy observation was that a majority of participants who self-reported having taken a physics course assigned lower confidence scores to their physics knowledge. In contrast, some participants with no physics course experience rated higher confidence scores in their knowledge. Nevertheless, the unexpected weak correlation between prior physics knowledge and metacognitive abilities is surprising, especially given ample evidence from previous studies emphasizing a robust connection between these two variables. For instance, a study (Coleman & Shore, 1991) recruited high school students and categorized them as either high performer or average performer based on their physics knowledge. According to the study, the high performers in physics exhibited significant differences from the average counterparts in metacognitive capabilities. High performers effectively monitored and assessed their problem-solving processes, promptly drawing on pertinent information acquired previously to assist in solving problems. Conversely, the average performers demonstrated less accurate monitoring of their problem-solving processes, primarily concentrating on the information presented in the problem, and making minimal efforts to integrate that information with their relevant prior knowledge. Therefore, future studies with larger sample sizes are warranted, given the previous research consistently highlighting the influence of individual differences in metacognitive learning behaviors among young learners.

Effectiveness of Metacognitive Prompts

The hypothesis proposing that metacognitive prompts would enhance participants' learning outcomes was refuted in the inferential statistical analysis. There was no significant difference in post-training performance between the control and experimental groups. Specifically, the experimental group exclusively received two metacognitive prompts: (i) a metacognitive cue prompting a comparison between pre-training and the subsequent bodily training task scheduled for administration following the metacognitive cue and (ii) metacognitive reasoning questions probing for parallels between the pre-training and bodily training tasks. Given the consistent emphasis in the literature on the importance of metacognitive abilities in resolving conflicts arising from the coexistence of competing theories in one's mind, why did the experimental group not demonstrate significantly improved performance in post-training, despite receiving metacognitive interventions? What key components were lacking in the metacognitive reasoning prompts that failed to help participants address conflicts?

The reported lack of significant effectiveness in metacognitive interventions can be interpreted from various perspectives. From a macroscopic perspective, the observed ineffectiveness may be attributed to insufficient statistical power due to a limited sample size ($N = 36$). The study's online platform may have also played a role, with younger participants potentially overlooking the unsupervised metacognitive cue. Additionally, there is a possibility of participants not fully grasping the purpose of the metacognitive instruction.

Despite the absence of statistical significance, however, it does not imply that they had no impact in triggering a conceptual transition among participants. From a microscopic perspective, it is noteworthy that participants who successfully identified a logical comparison between pre-training and bodily training tasks either maintained their initial correct answers or rectified their initial incorrect answers in the post-training phase. Concurrently, however, this perpetual transition also occurred in unintended directions; some participants changed their initial correct answers to incorrect ones in the post-training phase. This undesirable transition was observed in the experimental group, but even more frequently in the control group. Furthermore, specific participants who shifted from correct to incorrect responses altered their justifications, favoring impetus beliefs to rationalize their erroneous transition in the post-training phase. This underscores that while metacognitive interventions prompted a certain degree of conceptual transition, they fell short of providing clear guidance to prevent learners from reaching incorrect conclusions in a state of confusion.

Optimizing Metacognitive Support for Adolescent Learners: A Discussion

Concluding from the collected data, exploring ways to optimize metacognitive support for adolescents prompts a discussion aimed at addressing the following questions: what obstacles prevented participants from drawing analogies between their competing findings derived from distinct representations of force and motion? What hindered them from applying the insights gained from the bodily training tasks rooted in Newtonian mechanics when reevaluating the pre-training tasks? Given the observed lack of mature metacognitive abilities among adolescents, it is evident that they require more metacognitive support. However, what essential elements should such interventions incorporate to guarantee their effectiveness?

Firstly, it was notable that a high portion of participants did not rectify their initial incorrect answers, despite achieving a high rate of correct responses in bodily training tasks. This occurred either due to a failure to recognize conflicts or an inability to generalize their findings from the bodily training in the post-training phase. This phenomenon is not unique to the specific group of participants in this study. Previous research indicates that college students showed no ability to apply their findings from experiences when solving abstract problems (Kaiser et al., 1986). One argument suggests that individuals employ distinct reasoning approaches based on the context in which a problem is presented. For instance, individuals rarely engage in reasoning for problems related to daily life experience such as the bodily training tasks in the present study; instead, they generally rely on intuition, operating without a deliberate process of reasoning (Evans, 2010). Another claims that the challenge lies not in the inability to integrate findings but rather in the use of formal physical principles with inaccurate theories or the inclusion of irrelevant information in judgement such as using the velocity of a vehicle to forecast the falling trajectory of an object (Kaiser et al., 1986). The combination of the data collected in the study with previous research provides a valuable guidance for refining metacognitive support. It should emphasize the integration of learners' comprehension of a concept across diverse theories into a cohesive system aligned with the goals of formal physics education. Furthermore, metacognitive support should be tailored to actively involve learners in the reasoning process, especially when employing analogies of familiar experiences or examples to consolidate it into a scientific concept. This consideration is important, given that individuals may not inherently apply reasoning when approaching familiar problems. In this context, it can be deduced that the metacognitive cue of posing a question, as employed in this study, fell short of effectively engaging participants in active reasoning.

Secondly, another factor diminishing the effectiveness of the metacognitive intervention is that the study was conducted online, lacking interaction or timely feedback on participants' responses. This might result in a more noticeable disparity among adolescent participants, considering that they exhibited less maturity in their metacognitive abilities. Certainly, teachers can dynamically contribute to knowledge construction through discursive and social interaction (Vygotsky, 1980). Science education has been commonly taught through argumentation. Argumentation involves coordinating evidence and theory to either support or challenge an explanatory conclusion, model, or prediction (Erduran et al., 2015). It can serve as a vital discourse for bridging and consolidating competing theories in learners' understanding of a physics topic. In the specific context of employing argumentation to assist students in integrating analogies from common experiences into abstract problems, however, the structure of argumentation needs thoughtful consideration. Specifically, teachers should guide students to participate in dialectical argumentation, with a focus on how conflicting observations can be reasoned into a scientifically accurate theory. This argument gains support by a study that observed 153 whole-class argumentative discourse in secondary school science classrooms (Larrain et al., 2014). It reveals that students seldom engage in discussions about contradictory points of view but instead predominantly focus on justifying their perspectives.

While this study did not yield statistically significant results, possibly owing to the relatively small sample size, it does offer valuable insights into how secondary school students reason about a physics concept of force and motion with conflicting theories coexisting in their understanding and how they employ individual metacognitive abilities in the process of resolving such conflicts. The findings and generalizability of the results may be compromised since the sample might not adequately represent the diverse range of perspective or characters within the broader population of interest. Additionally, the study was conducted online without direct experiment supervision, and some data relied on self-assessment by adolescents. This could potentially introduce inaccuracies as it may hinder obtaining more precise data, particularly in cases where students may have misunderstood survey questions. Therefore, future research improving these components is recommended to achieve a comprehensive understanding.

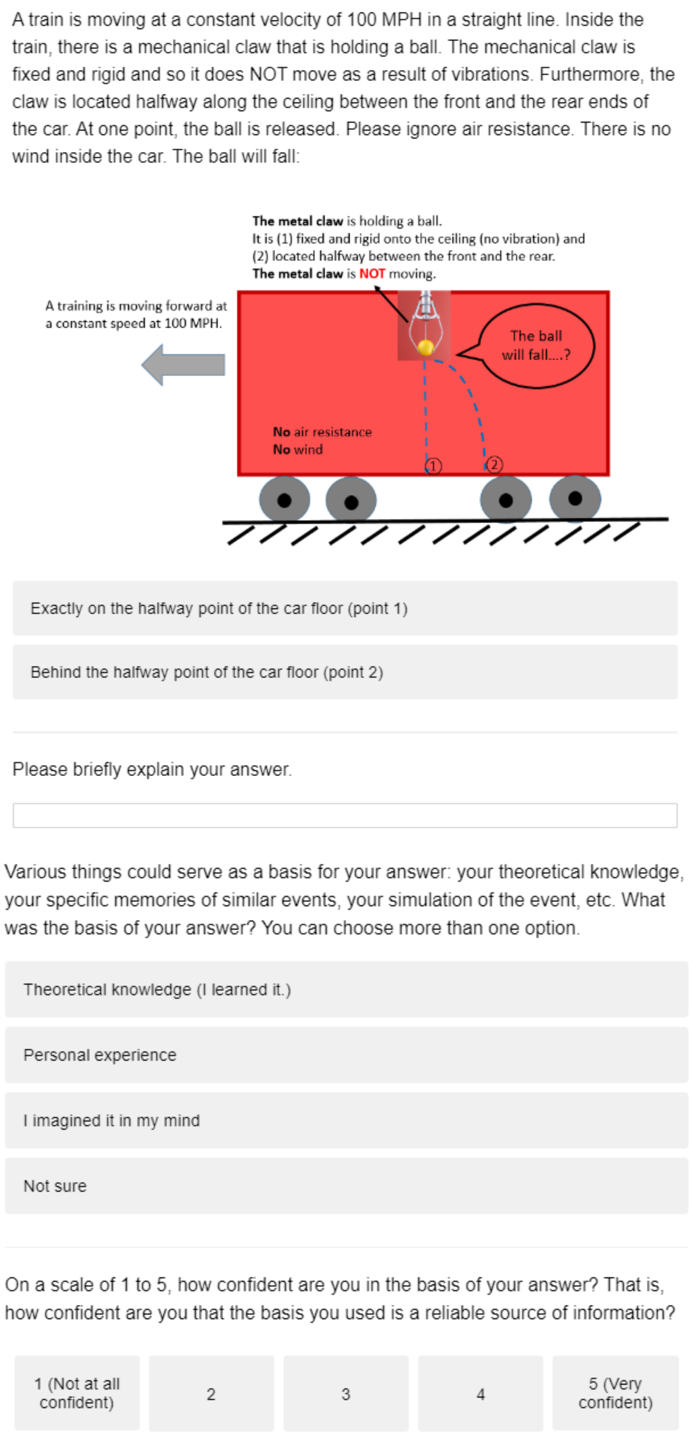
Appendix 1.

Thought Experiments on Force and Motion

The thought experiment on force and motion serves as a tool to improve the learning experience among participants by promoting the error detection and correction process. It is designed to elicit specific responses from participants (Bascandziev, 2023).

Participants engaged in four thought experiment tasks within each of the three training phases: pre-training, bodily training, and post-training. In each item, participants are tasked with making predictions, offering explanations, selecting a judgement base, and rating their confidence levels. The response options for all items are multiple choice, except for the explanation item. The task items in the post-training phase are identical to those administered in the pre-training phase.

Pre-training Thought Experiment Task Set (Q1)



A train is moving at a constant velocity of 100 MPH in a straight line. Inside the train, there is a mechanical claw that is holding a ball. The mechanical claw is fixed and rigid and so it does NOT move as a result of vibrations. Furthermore, the claw is located halfway along the ceiling between the front and the rear ends of the car. At one point, the ball is released. Please ignore air resistance. There is no wind inside the car. The ball will fall:

Exactly on the halfway point of the car floor (point 1)

Behind the halfway point of the car floor (point 2)

Please briefly explain your answer.

Various things could serve as a basis for your answer: your theoretical knowledge, your specific memories of similar events, your simulation of the event, etc. What was the basis of your answer? You can choose more than one option.

Theoretical knowledge (I learned it.)

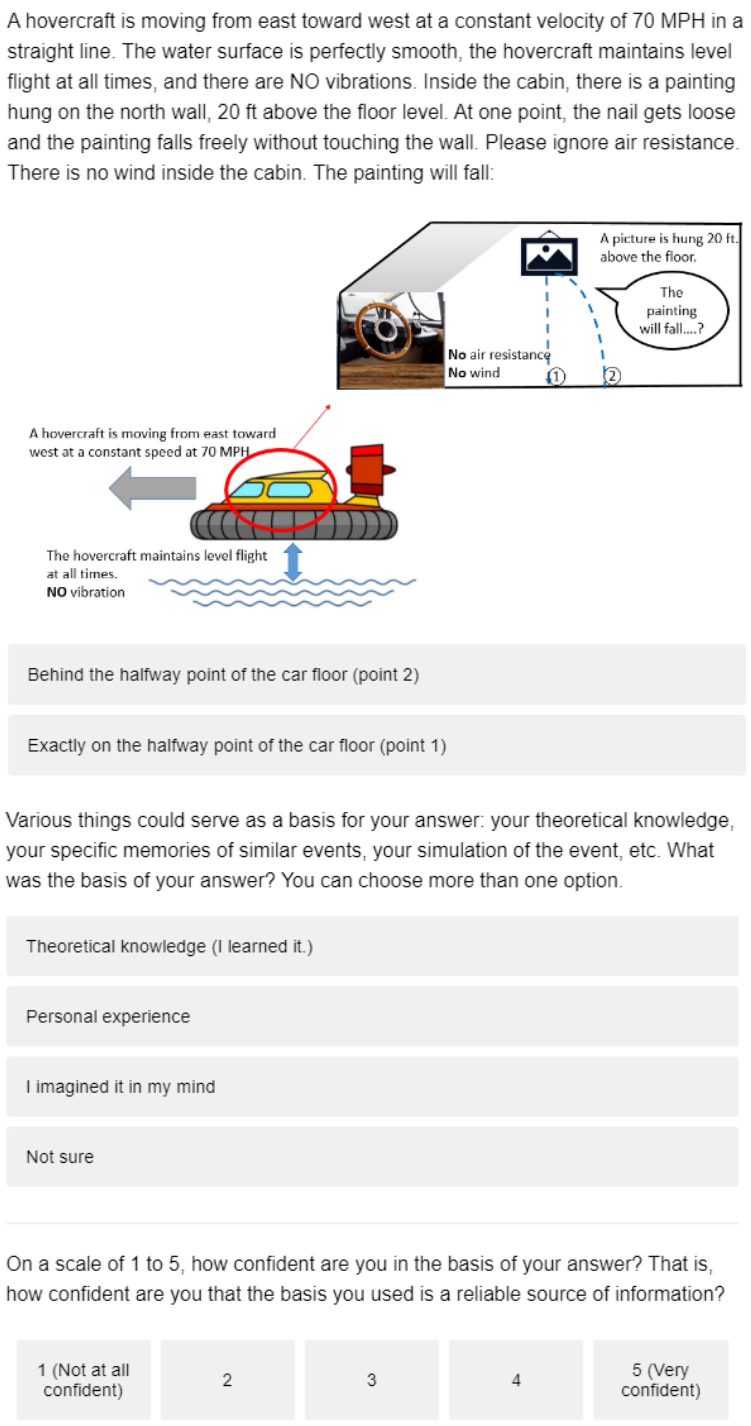
Personal experience

I imagined it in my mind

Not sure

On a scale of 1 to 5, how confident are you in the basis of your answer? That is, how confident are you that the basis you used is a reliable source of information?

Pre-training Thought Experiment Task Set (Q2)



A hovercraft is moving from east toward west at a constant velocity of 70 MPH in a straight line. The water surface is perfectly smooth, the hovercraft maintains level flight at all times, and there are NO vibrations. Inside the cabin, there is a painting hung on the north wall, 20 ft above the floor level. At one point, the nail gets loose and the painting falls freely without touching the wall. Please ignore air resistance. There is no wind inside the cabin. The painting will fall:

Behind the halfway point of the car floor (point 2)

Exactly on the halfway point of the car floor (point 1)

Various things could serve as a basis for your answer: your theoretical knowledge, your specific memories of similar events, your simulation of the event, etc. What was the basis of your answer? You can choose more than one option.

Theoretical knowledge (I learned it.)

Personal experience

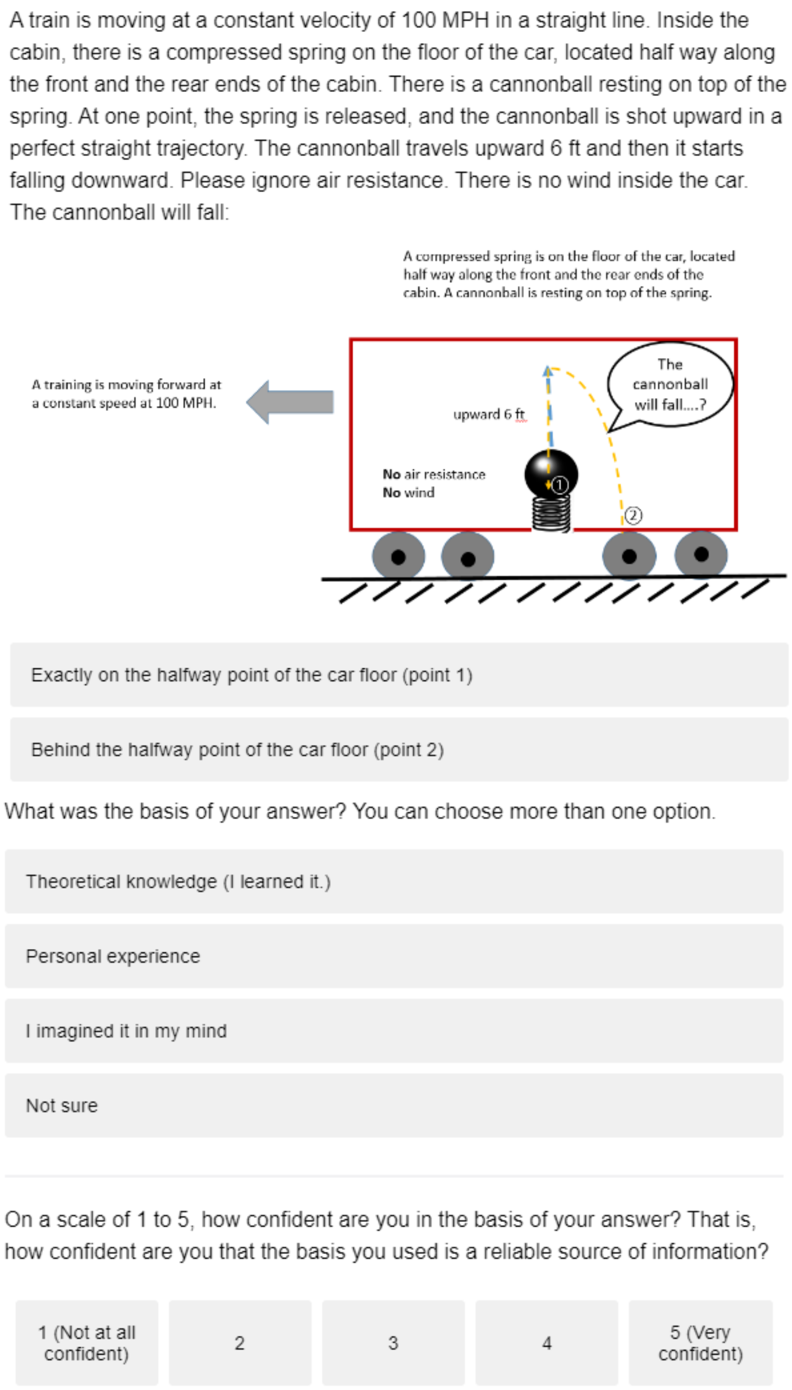
I imagined it in my mind

Not sure

On a scale of 1 to 5, how confident are you in the basis of your answer? That is, how confident are you that the basis you used is a reliable source of information?

1 (Not at all confident)	2	3	4	5 (Very confident)

Pre-training Thought Experiment Task Set (Q3)



A train is moving at a constant velocity of 100 MPH in a straight line. Inside the cabin, there is a compressed spring on the floor of the car, located half way along the front and the rear ends of the cabin. There is a cannonball resting on top of the spring. At one point, the spring is released, and the cannonball is shot upward in a perfect straight trajectory. The cannonball travels upward 6 ft and then it starts falling downward. Please ignore air resistance. There is no wind inside the car. The cannonball will fall:

Exactly on the halfway point of the car floor (point 1)

Behind the halfway point of the car floor (point 2)

What was the basis of your answer? You can choose more than one option.

Theoretical knowledge (I learned it.)

Personal experience

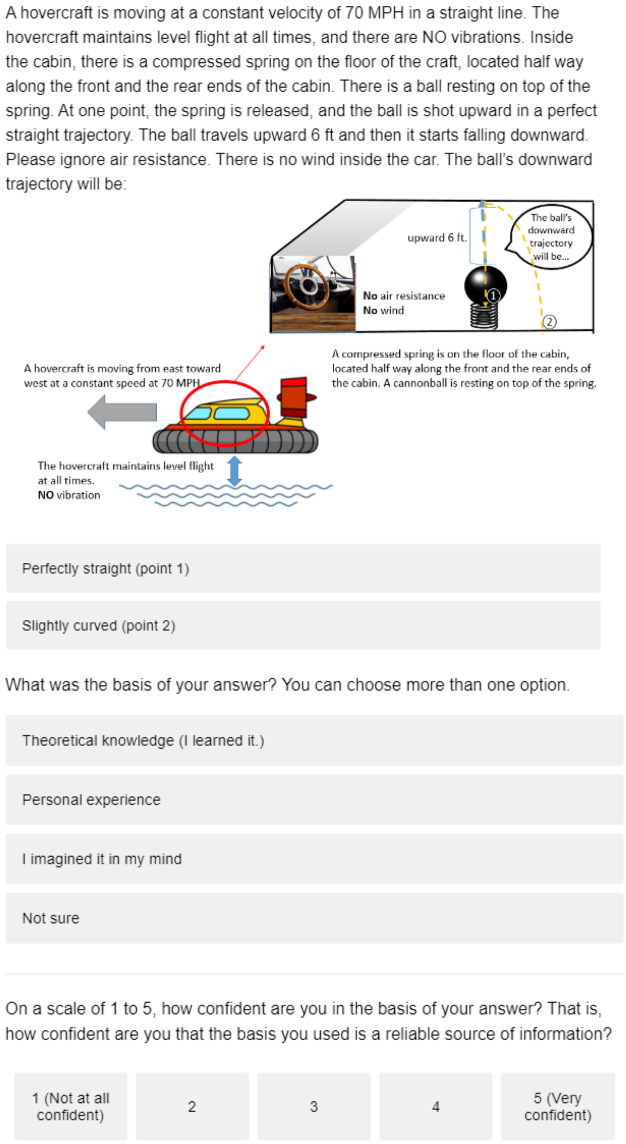
I imagined it in my mind

Not sure

On a scale of 1 to 5, how confident are you in the basis of your answer? That is, how confident are you that the basis you used is a reliable source of information?

1 (Not at all confident)	2	3	4	5 (Very confident)

Pre-training Thought Experiment Task Set (Q4)



A hovercraft is moving at a constant velocity of 70 MPH in a straight line. The hovercraft maintains level flight at all times, and there are NO vibrations. Inside the cabin, there is a compressed spring on the floor of the craft, located half way along the front and the rear ends of the cabin. There is a ball resting on top of the spring. At one point, the spring is released, and the ball is shot upward in a perfect straight trajectory. The ball travels upward 6 ft and then it starts falling downward. Please ignore air resistance. There is no wind inside the car. The ball's downward trajectory will be:

Perfectly straight (point 1)

Slightly curved (point 2)

What was the basis of your answer? You can choose more than one option.

Theoretical knowledge (I learned it.)

Personal experience

I imagined it in my mind

Not sure

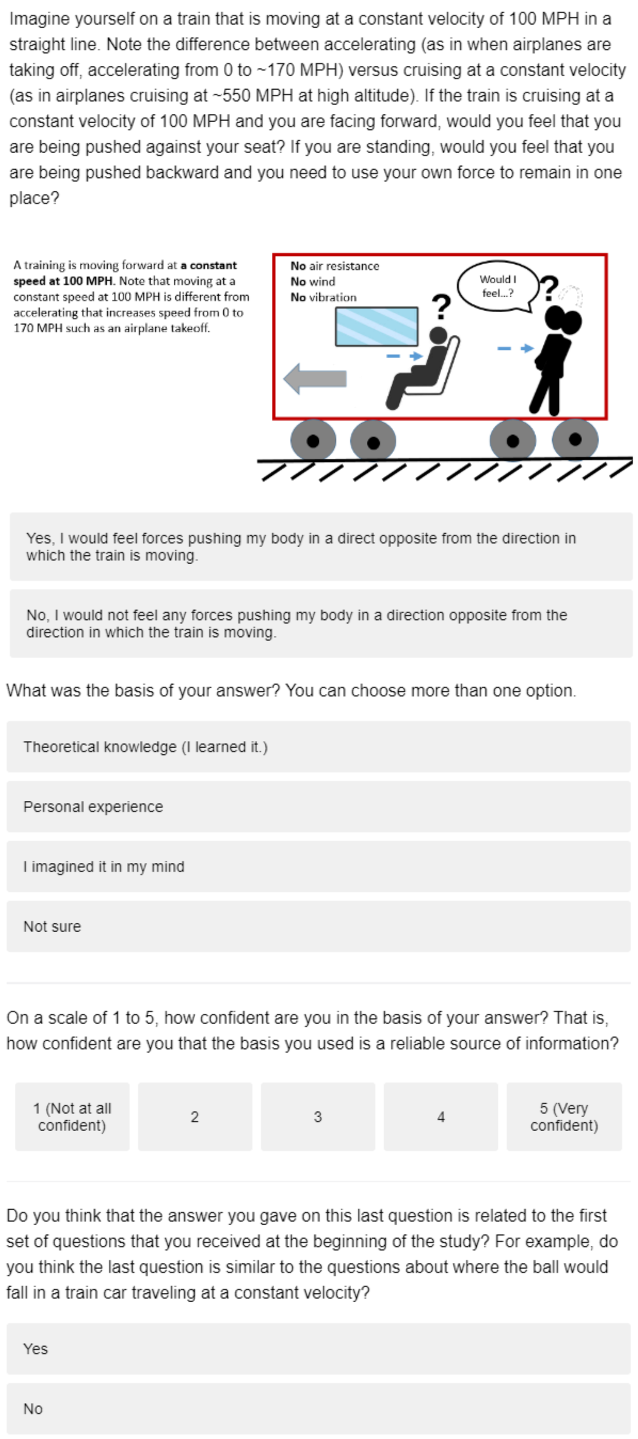
On a scale of 1 to 5, how confident are you in the basis of your answer? That is, how confident are you that the basis you used is a reliable source of information?

1 (Not at all confident)	2	3	4	5 (Very confident)

Figure 5. Thought Experiment Task Sets of Pre-and Post-Training Phase

Participants are tasked to predict the landing point of a moving object across four specified scenarios.

Bodily Training Thought Experiment Task Set (1)



Imagine yourself on a train that is moving at a constant velocity of 100 MPH in a straight line. Note the difference between accelerating (as in when airplanes are taking off, accelerating from 0 to ~170 MPH) versus cruising at a constant velocity (as in airplanes cruising at ~550 MPH at high altitude). If the train is cruising at a constant velocity of 100 MPH and you are facing forward, would you feel that you are being pushed against your seat? If you are standing, would you feel that you are being pushed backward and you need to use your own force to remain in one place?

A training is moving forward at **a constant speed at 100 MPH**. Note that moving at a constant speed at 100 MPH is different from accelerating that increases speed from 0 to 170 MPH such as an airplane takeoff.

Yes, I would feel forces pushing my body in a direct opposite from the direction in which the train is moving.

No, I would not feel any forces pushing my body in a direction opposite from the direction in which the train is moving.

What was the basis of your answer? You can choose more than one option.

Theoretical knowledge (I learned it.)

Personal experience

I imagined it in my mind

Not sure

On a scale of 1 to 5, how confident are you in the basis of your answer? That is, how confident are you that the basis you used is a reliable source of information?

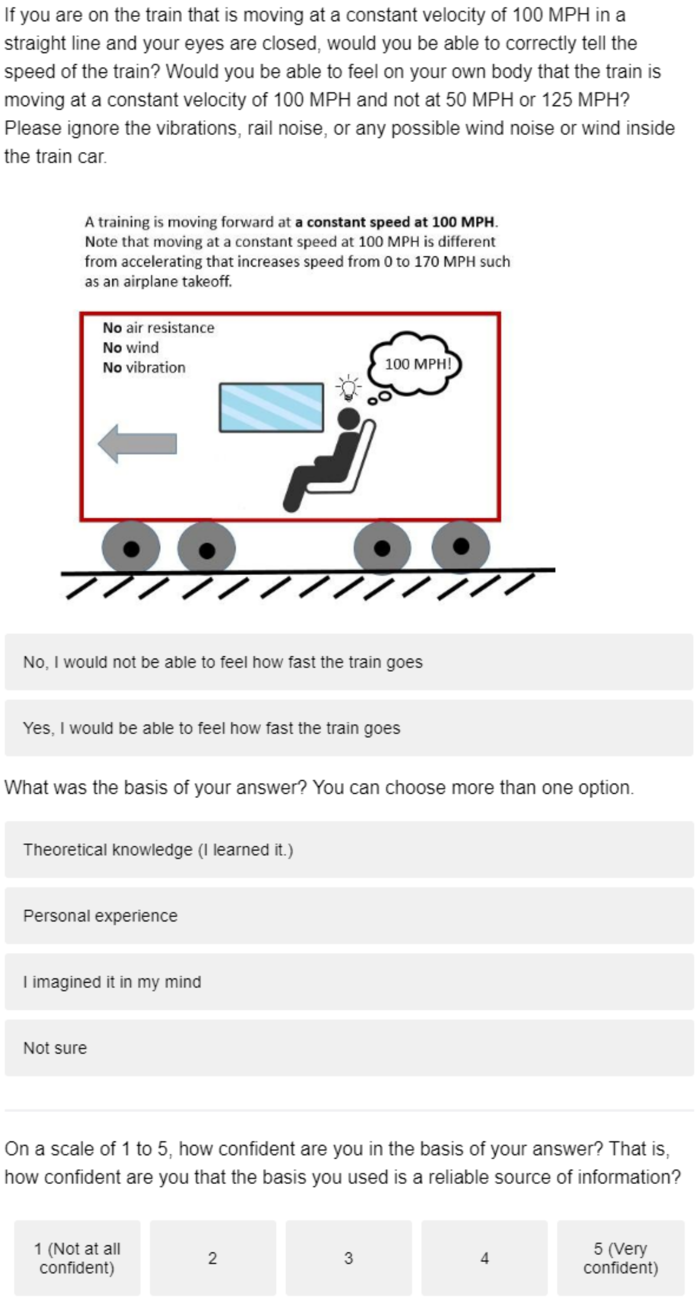
1 (Not at all confident)	2	3	4	5 (Very confident)

Do you think that the answer you gave on this last question is related to the first set of questions that you received at the beginning of the study? For example, do you think the last question is similar to the questions about where the ball would fall in a train car traveling at a constant velocity?

Yes

No

Bodily Training Thought Experiment Task Set (2)



If you are on the train that is moving at a constant velocity of 100 MPH in a straight line and your eyes are closed, would you be able to correctly tell the speed of the train? Would you be able to feel on your own body that the train is moving at a constant velocity of 100 MPH and not at 50 MPH or 125 MPH? Please ignore the vibrations, rail noise, or any possible wind noise or wind inside the train car.

A training is moving forward at **a constant speed at 100 MPH**. Note that moving at a constant speed at 100 MPH is different from accelerating that increases speed from 0 to 170 MPH such as an airplane takeoff.

No, I would not be able to feel how fast the train goes

Yes, I would be able to feel how fast the train goes

What was the basis of your answer? You can choose more than one option.

Theoretical knowledge (I learned it.)

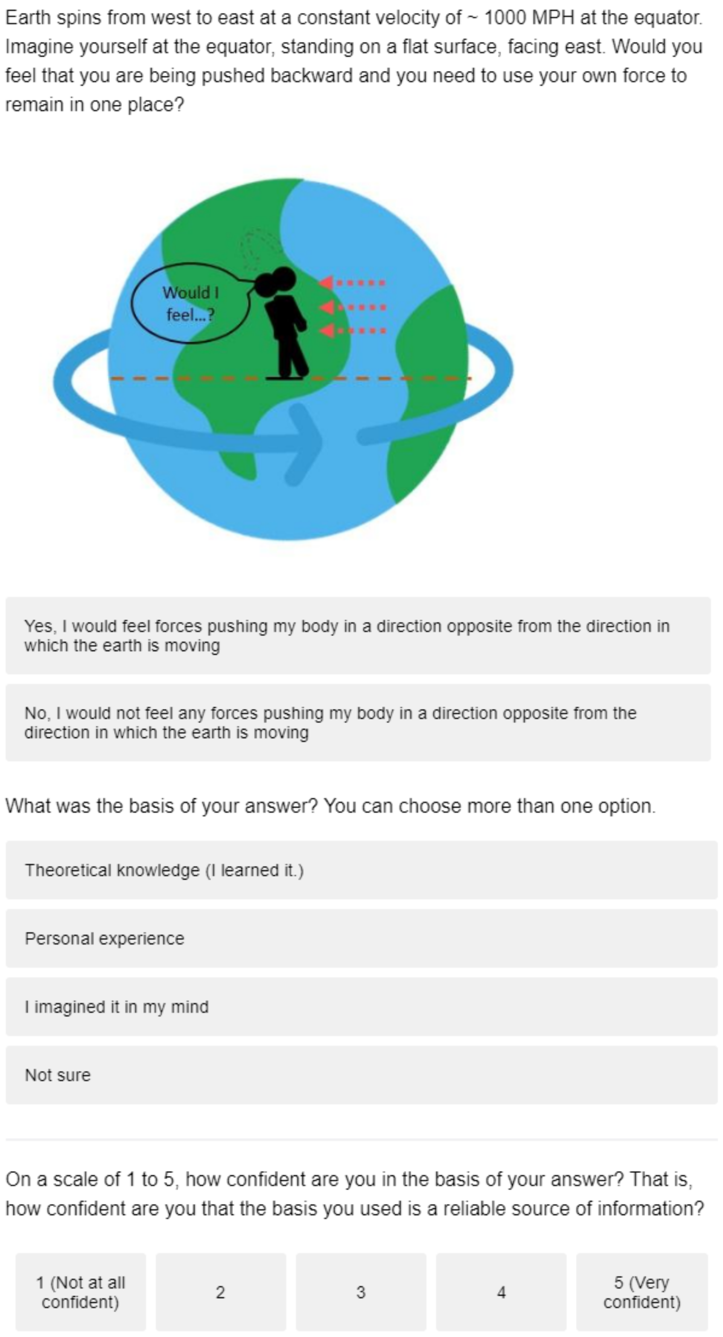
Personal experience

I imagined it in my mind

Not sure

On a scale of 1 to 5, how confident are you in the basis of your answer? That is, how confident are you that the basis you used is a reliable source of information?

Bodily Training Thought Experiment Task Set (3)



Earth spins from west to east at a constant velocity of ~ 1000 MPH at the equator. Imagine yourself at the equator, standing on a flat surface, facing east. Would you feel that you are being pushed backward and you need to use your own force to remain in one place?

Yes, I would feel forces pushing my body in a direction opposite from the direction in which the earth is moving

No, I would not feel any forces pushing my body in a direction opposite from the direction in which the earth is moving

What was the basis of your answer? You can choose more than one option.

Theoretical knowledge (I learned it.)

Personal experience

I imagined it in my mind

Not sure

On a scale of 1 to 5, how confident are you in the basis of your answer? That is, how confident are you that the basis you used is a reliable source of information?

1 (Not at all confident)	2	3	4	5 (Very confident)

Bodily Training Thought Experiment Task Set (4)

Imagine that you are in Singapore, which is close to the equator where earth spins at ~1000 MPH and then you travel to St. Petersburg, Russia where earth spins at ~500 MPH. Would you be able to feel on your own body how fast earth is spinning at these two locations? Would you be able to feel the difference in how fast you were going in Singapore compared to how fast you were going in St. Petersburg?

No, I would not be able to feel how fast earth goes

Yes, I would be able to fell how fast earth goes

What was the basis of your answer? You can choose more than one option.

Theoretical knowledge (I learned it.)

Personal experience

I imagined it in my mind

Not sure

On a scale of 1 to 5, how confident are you in the basis of your answer? That is, how confident are you that the basis you used is a reliable source of information?

1 (Not at all confident) | 2 | 3 | 4 | 5 (Very confident)

Figure 6. Thought Experiment Task Set of Bodily Training Phase

Participants are tasked to make prediction by utilizing their personal bodily experience across four specified scenarios.

Appendix 2.

The Junior Metacognitive Awareness Inventory Version B

	MAI: Item number and Item	Conceptual Affiliation
1	I am a good judge of how well I understand something.	K.C(D.K)
2	I can motivate myself to learn when I need to.	K.C(C.K)
3	I try to use strategies that have worked in the past.	K.C(P.K)
4	I know what the teacher expects me to learn.	K.C(D.K)
5	I learn best when I already know something about the topic.	K.C(C.K)
6	I draw pictures or diagrams to help me understand while learning.	R.C(Information)
7	I ask myself if I learned as much as I could have once I finish a task.	R.C(Evaluation)
8	I ask myself if I have considered all options when solving a problem	R.C(Monitoring)
9	I ask myself if I really need to learn before I begin a task	R.C(Planning)

	MAI: Item number and Item	Conceptual Affiliation
9	I ask myself if I really need to learn before I begin a task.	R.C(Planning)
10	I ask myself questions about how well I am learning while I am learning something new.	R.C(Monitoring)
11	I focus on the meaning and significance of new information.	R.C(Information)
12	I learn more when I am interested in the topic.	K.C(D.K)
13	I use my intellectual strengths to compensate for my weaknesses.	K.C(C.K)
14	I use different learning strategies depending on the situation.	K.C(C.K)
15	I ask myself periodically if I am meeting my goals.	R.C(Monitoring)
16	I find myself using helpful learning strategies automatically.	K.C(P.K)
17	I ask myself if there was an easier way to do things after I finish a task.	R.C(Evaluation)
18	I set specific goals before I begin a task.	R.C(Planning)

Note. Each item of Jr.MAI is categorized by its own conceptual affiliation. "K.C" stands for Knowledge of Cognition, which encompasses "D.K" (Declarative Knowledge), "C.K"(Conditional Knowledge), and "P.K"(Procedural Knowledge). "R.C" stands for Regulation of Cognition, which includes information management skill, evaluation, monitoring, and planning.

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