

MULTIDISCIPLINARY CO- DEVELOPMENT FOR SSI-BASED NEUROETHICS EDUCATION: APPLICATION TO THE BRAIN DOPING ISSUE WITH TDCS

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Abstract. *Developing socioscientific issues (SSI) education on emerging technologies such as neurotechnology confronts the challenge of distributed expertise, wherein requisite knowledge spans multiple domains—neuroscience, neuroethics, and pedagogy—that no single educator can possess. This study proposes Multidisciplinary Co-Development (MCD) as a methodological framework to address this challenge and applies it to an SSI-based neuroethics education on brain doping through transcranial direct current stimulation (tDCS) technology. A multidisciplinary team comprising experts in neuroethics, neuroscience, and public engagement collaboratively developed an education program guided by three MCD principles: distributed expertise recognition, dialogic knowledge integration, and boundary artifact facilitation. The program was piloted with 38 Korean university students, and data were collected through group activity artifacts and a questionnaire. Qualitative analysis showed that the MCD principles enabled effective cross-disciplinary knowledge integration through structured dialogue and shared artifacts. Participants demonstrated the ability to identify scientific, ethical, and social problems of brain doping and to propose varied solutions, suggesting that the program supports the development of civic competencies. These findings indicate that MCD offers a viable framework for addressing distributed expertise challenges in emerging technology-related SSI education and provides a systematic methodology for translating neuroethics research into educational practice.*

Keywords: *brain doping, distributed expertise, multidisciplinary co-development, neuroethics education, socioscientific issues (SSI)*

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Introduction

Emerging technologies are reshaping society faster than educational systems can respond. Students are increasingly confronted with decisions concerning brain stimulation devices, generative artificial intelligence, and genetic enhancement technologies, yet existing curricula offer limited guidance on these matters. This gap between technological development and curricular preparedness suggests that science education needs to expand beyond transmitting established scientific facts. While such transmission remains necessary, scholars have argued that it is no longer sufficient, and students also need the competency to reason through issues lacking expert consensus yet carrying significant societal implications (Roberts, 2007; Valladares, 2021). Socioscientific issues (SSI)-based education has emerged as a pedagogical response to this need, engaging students in deliberative processes that connect scientific understanding with ethical judgment (Högström et al., 2025; Zeidler et al., 2005).

Despite the growing body of research on SSI education, much of this work has remained concentrated on limited topics such as climate change, genetics, and public health (Högström et al., 2025; Viehmann et al., 2024). Emerging technologies such as artificial intelligence and neurotechnology have received little attention in SSI education. This limited attention may stem from the more complex challenges that these technologies pose compared to conventional SSI topics. Scientific knowledge in these fields is evolving rapidly, creating persistent uncertainty, while the relevant expertise spans multiple disciplines, making interdisciplinary integration difficult. These characteristics may present SSI educators with significant challenges, such as identifying reliable scientific knowledge in rapidly changing fields, concretizing abstract ethical and social issues, and navigating uncertainty across multiple disciplines.

Ethics education on emerging technologies, however, cannot be deferred. Public deliberation early in technological development, particularly before key design choices and regulatory frameworks become fixed, has provided citizens with greater opportunity to influence technological trajectories (Goering et al., 2021). Educational engagement, therefore, should begin while opportunities for democratic input remain open. For students to participate effectively in such deliberation as future citizens, they need to



understand both the scientific foundations and the ethical dimensions of the technology. This study argues that the core aim of ethics education on emerging technologies is to cultivate civic competency, which includes the ability to identify ethical and social issues surrounding technology, evaluate benefits and risks from a balanced perspective, and engage in deliberative decision-making regarding technology adoption and use.

Among emerging technologies, neurotechnology acutely demonstrates the urgency of SSI-based ethics education. Advanced neurotechnologies such as brain-computer interfaces and deep brain stimulation can transform human cognition and sensory experience, raising complex philosophical and societal issues concerning identity, autonomy, privacy, enhancement, and social equity (Goering et al., 2021). Among various neurotechnologies, this study selects transcranial direct current stimulation (tDCS), a non-invasive brain stimulation technology, and constructs the brain doping issue through tDCS as an SSI topic. Brain doping refers to the use of neurotechnology by healthy individuals for cognitive enhancement, which relates to students' everyday concerns, such as academic achievement while meeting core SSI requirements, as it sits at the intersection of scientific understanding and social value judgment.

Developing such SSI-based neuroethics education, however, presents a structural challenge. This development requires the integration of expertise that no single discipline possesses: neuroscientific knowledge, competence in articulating ethical considerations, and pedagogical expertise. These areas of expertise do not reside in any single field but have been distributed across distinct expert groups (Brown et al., 1993; Jadallah & Ballard, 2025). This “distributed expertise” presents a significant obstacle to curriculum development. Conventional approaches, such as expert consultation, have typically involved specialists contributing individually at separate stages, limiting organic knowledge integration through sustained interaction (Lenhart & Bouwma-Gearhart, 2022; Voogt et al., 2011). To address this limitation, this study proposes Multidisciplinary Co-Development (MCD) as a methodological response. In MCD, experts from different fields collaborate continuously across disciplinary boundaries to co-construct an integrated understanding as well as engage in discussions within their respective domains. The focus of this study is twofold: first, to propose MCD as a methodological framework that addresses the challenges of distributed expertise in SSI education concerning emerging technologies, and second, to examine its application through the development and implementation of an SSI-based neuroethics education on brain doping.

Theoretical Background

SSI Education and its Challenges

SSI-based education enhances scientific literacy, including democratic civic competencies, beyond the acquisition of science knowledge. Zeidler et al. (2005) have argued that the SSI approach integrates understanding of the nature of science, argumentation skills, and moral reasoning more effectively than the Science–Technology–Society (STS) approach. Subsequent systematic reviews have confirmed that SSI education enhances higher-order thinking skills, moral sensitivity, and argumentation abilities (Högström et al., 2025; Viehmann et al., 2024). These outcomes align with what Roberts (2007) has termed functional scientific literacy, which emphasizes informed decision-making across diverse social and scientific contexts.

Despite these documented benefits, the implementation of SSI education faces several barriers. Prior studies have identified major obstacles, including insufficient teacher knowledge, inadequate pedagogical skills, anxiety about controversial topics, and institutional pressures such as time constraints and standardized testing requirements (Day & Bryce, 2011; Ekborg et al., 2013; Hancock et al., 2019; Sadler et al., 2006). This study argues that these barriers reflect the inherently interdisciplinary nature of SSI. Because SSI spans traditional disciplinary boundaries (Zeidler, 2014), effective instruction requires not only mastery of relevant science content but also awareness of social considerations and willingness to engage with uncertainty (Presley et al., 2013). Teachers' knowledge deficits, therefore, may reflect not individual shortcomings but the structural reality that the expertise SSI requires is distributed across specialized domains. Research on co-teaching illustrates this distribution. For example, Karahan and Roehrig (2017) have found that SSI-based instruction draws on science teachers' expertise in scientific content and social studies on teachers' knowledge of social, cultural, and ethical dimensions.

These challenges should not be attributed to individual teachers' inadequacy. Chen and Xiao (2021) have emphasized that teachers' success in implementing SSI is contingent upon receiving concrete guidance and collaborative support from key stakeholders, including policymakers, teacher educators, and school administrators. What is needed, therefore, is not merely enhanced individual competence but a systematic methodology that enables experts from different domains to collaboratively develop SSI curricula.



Limitations of Existing Approaches to Distributed Expertise

Various approaches have been developed to address the challenges posed by distributed expertise in SSI education. This study categorizes three approaches based on who assumes the primary role in resolving these challenges.

The first is the expert consultation approach, in which external experts assume the primary role while teachers are positioned as knowledge recipients. An analogous model can be observed in international brain science projects, where neuroethics expert groups have reviewed the ethical implications of research and developed guidelines (Greely et al., 2018; Salles & Farisco, 2020). This approach, however, presents several limitations. Expert knowledge may become disconnected from the context of educational practice, and one-time consultations make it difficult to respond to rapidly evolving scientific and technological developments.

The second is the teacher professional development approach, in which teachers assume the primary role as learners and strengthen their SSI teaching competencies through structured programs. Such programs typically have provided activities such as collaborative curriculum design, exploration of SSI sample units, and development of pedagogical content knowledge (Eidin & Shwartz, 2023; Hancock et al., 2019). This approach, however, requires considerable investment of time and resources. When the scope of specialized knowledge is extensive, professional development alone may be insufficient to bridge the competency gap (Yoon et al., 2023).

The third is the educational materials development approach. Although materials developed through systematic expert-driven design have high-quality content, they may not align with teachers' specific contexts or students' needs. Furthermore, when teachers are relegated to merely implementing materials, opportunities for professional growth become limited (Remillard, 2005).

The three approaches outlined share common limitations. These include reliance on unidirectional knowledge transmission, emphasis on individual capacity accumulation, and temporal separation between the development and implementation phases. What these approaches lack is a mechanism for sustained, dialogic interaction among experts from different domains throughout the curriculum development process.

These limitations are amplified in SSI education on emerging technologies. The epistemological challenges inherent to SSI, including contested evidence, value-laden judgments, and irreducible uncertainty (Levinson, 2006), intensify when the underlying science itself remains rapidly evolving. Neurotechnology, the focus of this study, exemplifies this complexity.

Knowledge instability poses the most immediate difficulty. The unprecedented pace of advancement in neuroscience and neurotechnology means that findings evolve so rapidly that even specialists struggle to keep abreast of new developments (Jwa et al., 2023). This places additional pedagogical burden on teachers, who already face the task of addressing uncertain scientific claims. Beyond this empirical complexity, neurotechnology has raised profound philosophical questions concerning the physical basis of the self, the nature of free will, and the moral status of artificially enhanced cognition (Goering et al., 2021). Translating such abstract concepts into meaningful classroom discussions requires considerable pedagogical expertise. Adding to this complexity is the multidisciplinary nature of neuroethics scholarship, which analyzes ethical, legal, social, and cultural implications (ELSCI) by integrating such domains as neuroscience, philosophy, law, and sociology (Choi et al., 2025; Jwa et al., 2023).

Multidisciplinary Co-Development as a Methodological Framework

Co-design, as an approach to educational research and development, positions practitioners as co-designers of solutions to problems and has typically been characterized by dyadic collaboration between researchers and teachers aimed at improving classroom learning environments (Penuel et al., 2011). SSI education on emerging technologies, however, presents challenges beyond this dyadic framework. Addressing topics such as brain doping requires the collaborative integration of expertise from multiple domains, including neuroscience, neuroethics, and education, that cannot be achieved through any single researcher-teacher partnership. This study proposes MCD as a methodological framework that extends co-design to multidisciplinary collaboration. In MCD, disciplinary experts co-construct knowledge through mutual learning, guided by three core principles: distributed expertise recognition, dialogic knowledge integration, and boundary artifact facilitation.

Distributed expertise recognition constitutes the foundational principle of MCD. This principle acknowledges that the knowledge and skills necessary for addressing complex tasks are distributed across multiple expert communities. It further requires that these diverse forms of expertise be equally respected. Karahan and Roehrig (2017),



for instance, have found that collaborative SSI curriculum development between a science teacher and a social studies teacher has been grounded in mutual recognition that neither discipline alone can address all dimensions of the issues. In interdisciplinary educational program development, genuine collaboration becomes possible when participants value diverse disciplinary perspectives and respect the scope and uniqueness of knowledge from other fields (Lenhart & Bouwma-Gearhart, 2022). Drawing on this principle, the MCD approach in this study adopts a structure comprising three platforms, neuroethics, neuroscience, and public engagement, each representing a specific domain of expertise. This structure ensures that the scientific expertise of neuroscientists, the normative analytical capabilities of ethicists, and the pedagogical skills of educators are equally valued and systematically integrated into the development process.

Dialogic knowledge integration, built upon this horizontal relationship, refers to the process through which diverse experts engage in sustained dialogue to co-construct an integrated understanding that transcends individual disciplinary perspectives. Unlike unidirectional knowledge transmission, dialogic integration emphasizes reciprocal exchange wherein experts not only contribute their domain-specific knowledge but also actively learn from and respond to perspectives from other disciplines (Voogt et al., 2011). Effective dialogue among experts from different disciplinary communities, however, requires connecting mechanisms that traverse community boundaries. Wenger (2000) has termed such boundary-crossing individuals “brokers.” These actors belong to multiple communities of practice simultaneously, enabling them to reduce linguistic and conceptual barriers and help participants construct shared meaning. In this study, each platform pursues in-depth independent discussions while also participating in cross-platform collaboration through regular working group meetings, as described in the Methods section. Throughout this process, brokers play a pivotal role in bridging disciplinary boundaries and coordinating the integration of disciplinary knowledge through ongoing dialogue.

Boundary artifact facilitation, the third principle of MCD, emphasizes the role of tangible artifacts in enabling and sustaining collaborative processes. Rather than focusing solely on the creation of boundary artifacts, this principle highlights how boundary artifacts actively facilitate communication, negotiation, and knowledge integration among diverse experts. Star and Griesemer (1989) have defined boundary objects as artifacts that different communities of practice can share and utilize meaningfully within their respective contexts. Kim and Herbert (2012) have demonstrated that, in scientist–teacher professional learning communities, inquiry resources developed by scientists function as boundary artifacts in teachers’ instructional design, bridging divergent interpretations of inquiry. In this study, the XYZ-axis matrix and the ELSCI scaffolding tool serve as boundary artifacts. In particular, the XYZ-axis matrix, developed by Jwa et al. (2023), functions as the core boundary artifact, providing a shared framework for content analysis. Whereas MCD addresses the “how” of educational program development, the XYZ-axis matrix specifies “what” issues to address. Through collaboration among experts in neuroscience, neuroethics, and education, these boundary artifacts facilitate the production of comprehensive educational materials that would be challenging for individual experts to develop independently.

The three principles outlined above are interconnected. Distributed expertise recognition provides the foundation for the other principles. Building upon this foundation, brokers facilitate communication between communities during the integration process, while boundary artifacts function as mediators that enable the synthesis of distributed expertise into tangible educational outcomes. Through the synergy of these interconnected principles, MCD provides a systematic framework for harnessing distributed expertise in the development of SSI-based neuroethics education.

Based on the discussion above, this study poses the following research questions:

1. How does MCD address the challenges posed by distributed expertise in the development of SSI-based neuroethics education programs?
2. What civic competencies do participants demonstrate through the neuroethics education program on brain doping developed via MCD?

Research Methodology

General Background

South Korea enacted the Brain Research Promotion Act in 1998 to advance brain science as a national priority (Kang et al., 2023). Following the launch of the Korea Brain Initiative in 2017, the Korean government prioritized governance systems to address the societal implications of neurotechnology (Jeong et al., 2019). Within this policy context, the Korea Brain Research Institute (KBRI) established a neuroethics research group (Jwa et al., 2023).



This study was conducted as part of a neurotechnology ELSI research project (2019–2023) funded by the National Research Foundation of Korea. Although the official project title used ELSI (ethical, legal, and social implications), the research team adopted ELSCI as the analytical framework, which extends ELSI by incorporating culture as a distinct dimension (Choi et al., 2025; Jwa et al., 2023). The project operated through three specialized platforms: neuroethics, neuroscience, and public engagement. This structure provided the institutional basis for implementing MCD principles.

To examine the applicability of the MCD framework, this study adopted an exploratory design with two components: development of an SSI-based neuroethics education program through MCD, and pilot implementation to explore participants’ civic competencies. The study was approved by the Institutional Review Board of Kangwon National University (Approval Number: KWNUIRB-2022-01-003-003).

Participants

The pilot implementation was conducted with three groups across different contexts: general citizens, university students, and science teachers. Among these, 38 university students constituted the primary sample for analyzing participants’ civic competencies. University students were selected because the brain doping issue is likely to resonate with them, given the academic pressures they face. They also represented both learners and future citizens who would likely confront neurotechnology-related decisions. The university course setting also provided controlled implementation conditions.

The sample comprised students enrolled in a liberal arts course on science and technology at a national university in South Korea. It included 27 males (71.1%) and 11 females (28.9%). Of these, 37 were first-year students, and one was a second-year student. By major, 37 were from the Natural Sciences Track of the College of Liberal Studies, and one was from the Department of Bio-Industry Engineering. Participants were organized into eight small groups of four to five members for collaborative discussion. Before participating, all participants were informed of the research purpose and procedures and provided written informed consent.

Instruments and Procedures

The educational program was developed primarily by the public engagement platform in collaboration with experts from the other two platforms (Table 1). Reflecting MCD’s principle of distributed expertise recognition, they participated as equal partners in working group meetings.

Table 1
Platform-Specific Composition of the Multidisciplinary Co-Development (MCD) Team

Platform	Number	Disciplinary Background
Neuroethics	6	Philosophy (1), Humanities (1), Psychology (1), Law (1), Media Studies (1), Medical Ethics (1, PM)
Neuroscience	2	Neuroscience (2, one of whom is PM)
Public Engagement	6	Science Education (3), Science Communication (2), Science Education Research (1)

Note. PM = Project Manager. The PM holds dual affiliation with the neuroethics and neuroscience platforms as both a medical ethicist and a neuroscientist.

Within this structure, two brokers facilitated cross-platform communication (Wenger, 2000). One was the Project Manager (PM), a medical ethicist and neuroscientist affiliated with both the neuroethics and neuroscience platforms. The PM bridged all three platforms by regularly attending meetings of the public engagement platform. The PM also served as a lecturer during program implementation. The other broker was a science education researcher from the public engagement platform, specializing in SSI. With a research background in philosophy of science, this researcher attended meetings of the neuroethics platform.

The public engagement platform comprised six members: one science education researcher with expertise in SSI, three science teachers (two from middle school and one from high school), and two science communication practitioners specializing in science theater and scriptwriting. These members had gained experience in public

engagement and civic program development through their work with the education committee of a science and technology civic organization.

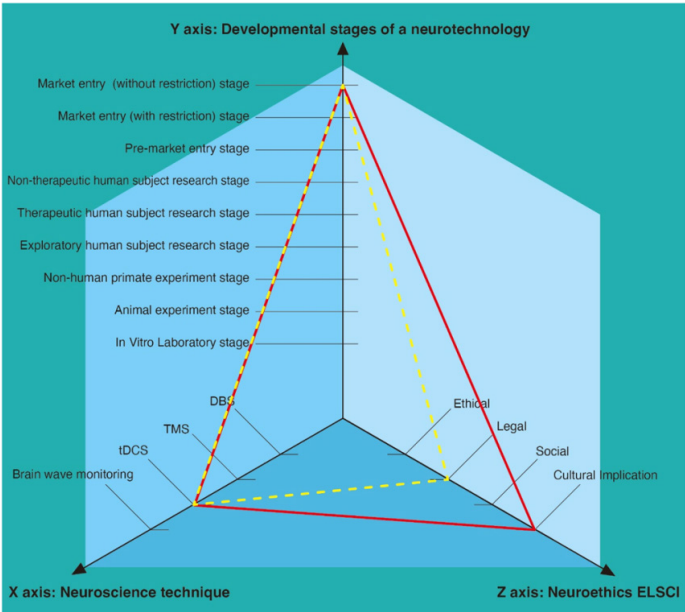
The program development followed five stages (Table 2). These stages modified Jwa et al.’s (2023) 10-step neuroethics ELSCI workflow for educational purposes. The description below highlights stages where MCD principles were central.

Table 2
Program Development Stages with Applied MCD Principles

Stage	Title	Main Activities	Applied MCD Principles
1	Goal Setting	Literature-based objective definition; Cross-platform goal consensus	Distributed expertise recognition
2	Topic Selection	XYZ-axis analysis (technology, maturity, ELSCI); SSI criteria verification	Boundary artifact facilitation, Dialogic knowledge integration
3	Interdisciplinary Knowledge Integration	Platform meetings + cross-platform working groups; Broker-mediated communication	Distributed expertise recognition, Dialogic knowledge integration
4	Educational Materials Development	Cross-platform review (accuracy, validity, appropriateness); Boundary artifact development	Boundary artifact facilitation, Dialogic knowledge integration
5	Pilot Implementation	Phased implementation (citizens → students → teachers); Feedback-driven refinement	Dialogic knowledge integration

In stage 2 (Topic Selection), the XYZ-axis matrix (Jwa et al., 2023) served as a boundary artifact, enabling experts from the three platforms to integrate their respective expertise with a shared analytical framework. This matrix consists of three dimensions: the X-axis represents a specific target neurotechnology, the Y-axis indicates the developmental maturity of the technology across nine stages from laboratory research to unrestricted market entry, and the Z-axis encompasses ethical, legal, social, and cultural implications (Figure 1).

Figure 1
XYZ-Axis Matrix Framework



Note. From "Ethical, legal, social, and cultural implications of the non-clinical use of transcranial direct current stimulation (tDCS) in Korea and Japan," by S. Choi, A. S. Jwa, J. Shim, S. Kim, J. Eom, Y. Takimoto, E. Nakazawa, and Y.-J. Ryu, 2025, *Neuroscience Research*, 219, p. 3 (<https://doi.org/10.1016/j.neures.2025.104951>). Licensed under CC BY-NC-ND 4.0.



Using this matrix, the teams selected tDCS as the focal technology. Along the X-axis, tDCS exhibits key characteristics including portability, low cost, and accessibility through online markets and DIY assembly (Choi et al., 2025). On the Y-axis, which assesses technological maturity based on the rigor of scientific evidence (Jwa et al., 2023), tDCS occupies an ambiguous position. While some studies have suggested cognitive benefits, others have yielded inconsistent results or have failed to replicate findings (Choi et al., 2025). Despite this uncertainty, tDCS has reached “market entry without restriction,” meaning devices are already available to the general public without regulatory oversight. This gap between scientific ambiguity and market availability makes ELSCI examination particularly urgent. Along the Z-axis, multilayered ELSCI issues emerged, including safety concerns from unregulated use, fairness questions regarding cognitive enhancement in competitive academic environments, and legal ambiguities surrounding non-medical applications. These characteristics meet established SSI criteria (Levinson, 2006). Brain doping through tDCS constitutes a current and controversial issue, given ongoing public debates about cognitive enhancement.

In stage 3 (Interdisciplinary Knowledge Integration), experts developed integrated understanding through platform-specific and cross-platform meetings. During platform-specific meetings, the public engagement group studied the scientific content and examined ethical issues related to brain doping. At cross-platform meetings, they raised questions and offered suggestions from a pedagogical perspective. Throughout this process, the project manager actively facilitated discussions, introducing relevant content and guiding the conversation.

In stage 4 (Educational Materials Development), the public engagement group led program design. Members reviewed relevant resources and shared their prior experiences with educational programs at civic organizations in science and technology contexts. This background informed their decisions about target civic competencies and appropriate difficulty levels. After determining the overall flow, selecting key activities, and drafting learning materials, the group sought feedback from the other platforms to verify scientific accuracy, ethical validity, and pedagogical appropriateness.

In stage 5 (Pilot Implementation), the science education researcher from the public engagement platform delivered the program at the university site. This arrangement minimized discrepancies between the intended curriculum and classroom implementation. Participants completed six activities across three stages (see Table 3 in the Results section).

Data Analysis

Two types of data were collected from group activity artifacts and a post-implementation questionnaire. Artifacts included worksheets for problem identification and solution development, capturing how participants applied the ELSCI scaffolding tool and developed solutions. The questionnaire consisted of six items measuring overall satisfaction, knowledge acquisition, problem recognition, interest development, solution development, and future participation intention on a 5-point Likert scale. Of the 38 participants, 35 completed the questionnaire. Descriptive statistics (means, standard deviations) and frequency distributions were calculated for each questionnaire item.

Qualitative analysis addressed two aspects of participants’ civic competencies. Problem identification was analyzed at the individual level ($N = 38$), with frequencies calculated across the five analytical perspectives of the ELSCI scaffolding tool: fairness violation, technological influence, external coercion, imitation effects, and health and safety risks. Solution development was analyzed at the group level ($N = 8$), with solutions classified into four domains: regulatory and institutional frameworks, technological safety measures, social equity measures, and educational approaches. Initial categories were derived from the neuroethics literature (Goering et al., 2021; Jwa et al., 2023) and refined to incorporate emerging themes in participant responses (Thomas, 2006). Analytic memos were maintained throughout the coding process to document coding decisions (Miles et al., 2020). To enhance interpretive validity, a qualitative methodology expert reviewed the analysis through peer debriefing sessions (Lincoln & Guba, 1985).

Methodological Limitations

This pilot study adopted a single-group design to examine the feasibility of the MCD approach. The design aimed to clarify how MCD operated and to explore its educational potential, rather than to establish causal claims regarding program effects. Although 38 university students constituted the primary sample, pilot implementations with general citizens and science teachers were also conducted to assess broader applicability. Interpretive limitations of this design are addressed in the discussion section.



Research Results

The Developed Educational Program

The SSI-based neuroethics education program on brain doping consisted of three stages and six activities, based on the SSI teaching and learning model proposed by Sadler et al. (2017). Table 3 presents the program structure.

Table 3
Structure of the Brain Doping Education Program

Stage	Activity	Description	SSI Teaching-Learning Elements
1: Encounter	A	Expert lecture: Doping concept, tDCS mechanisms, sports applications, regulatory status	Issue encounter, Science ideas
	B	Decision-making experience as consumers: Viewing 'BrainUp' home shopping video followed by asking participants to express purchase intention	Personal relevance, Social dimensions awareness
2: Engage	C	Sports doping analysis: Applying ELSCI scaffolding tool to familiar sports cases	Socioscientific reasoning, Multi-perspective analysis
	D	Brain doping analysis: Applying ELSCI scaffolding tool to tDCS-based brain doping to identify contextualized issues and problems	Contextual application, Socioscientific reasoning
3: Synthesize	E	Solution development: Group activity to develop solutions to the identified problems with the aids of alternative cards and elaboration cards	Decision-making, Developing solutions and alternatives
	F	Deliberation and reflection: Inter-group presentations and discussion	Argumentation, Synthesis

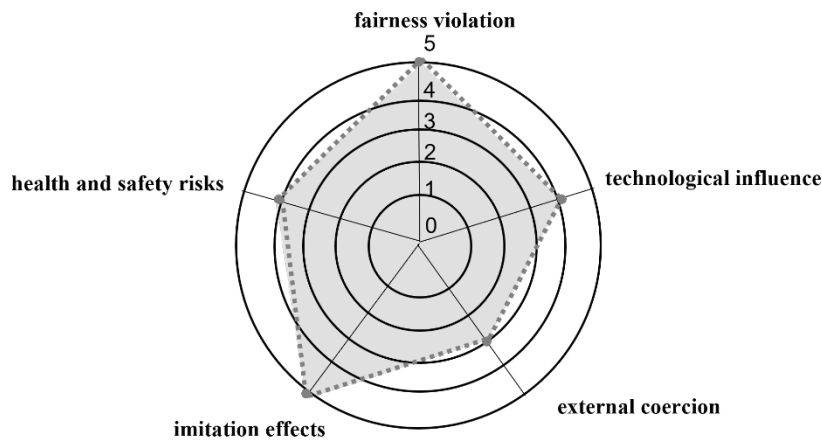
In the Encounter stage, participants attended an expert lecture on the scientific and ethical dimensions of neurotechnology (Activity A). They then viewed a fictional product video featuring a tDCS-based device called BrainUp to decide whether to purchase it (Activity B). These activities established scientific understanding and personal relevance. In the Engage stage, participants applied the ELSCI scaffolding tool first to sports doping cases (Activity C) and then to tDCS-based brain doping (Activity D), identifying contextualized issues and problems associated with each. In the Synthesize stage, they developed solutions (Activity E) and deliberated through inter-group presentations and discussion (Activity F).

This three-stage structure reflected a scaffolded progression from familiar to novel contexts. The Engage stage, in particular, began with sports doping cases before addressing tDCS-based brain doping, enabling participants to transfer their analytical framework to a less familiar domain. The Synthesize stage employed the alternative cards to widen participants' solution options and the elaboration cards to prompt them to concretize their solution proposals.

Two program components illustrated how the MCD principles were operationalized. The BrainUp video (Activity B) exemplified the integration of distributed expertise into a single educational artifact. The video presented a fictional home shopping advertisement for a tDCS device, incorporating three dimensions of expertise. It integrated neuroscientific accuracy in efficacy claims, ethical scenarios depicting information asymmetry and consumer vulnerability, and a familiar commercial format to establish personal relevance for learners.

The ELSCI scaffolding tool (Activities C and D) functioned as a boundary artifact, providing a shared framework for analyzing neuroethical issues from multiple perspectives. The tool comprised five analytical perspectives—fairness violation, technological impact, external coercion, imitation effects, and health and safety risks—each addressing contextualized ELSCI dimensions. Fairness violation, for example, encompassed ethical concerns about equity and social implications of access inequality, while external coercion addressed both legal and ethical issues regarding autonomy and voluntariness. This design integrated input from experts across the three platforms. In Activity C, the tool employed a pentagonal radar chart (see Figure 2) to visualize group consensus scores (0–5 points) across the five perspectives. The resulting polygon served as a visual profile of each case's ethical complexity, facilitating comparison across cases and analytical perspectives. As pedagogical scaffolding (Wood et al., 1976), the tool helped learners navigate complex concepts and engage in integrative thinking.



Figure 2*Radar Chart Visualization of the ELSCI Scaffolding Tool*

Note. The tool comprises five analytical perspectives: fairness violation, technological influence, external coercion, imitation effects, and health and safety risks. Groups assigned severity scores from 0 (no concern) to 5 (highest concern) for each perspective through consensus discussion. The shaded pentagon represents a hypothetical case analysis profile.

Pilot Implementation Results

Participants' responses to the post-program questionnaire indicated overall positive engagement with the program. Table 4 presents the means and standard deviations for the six questionnaire constructs, and Figure 3 displays the response distributions.

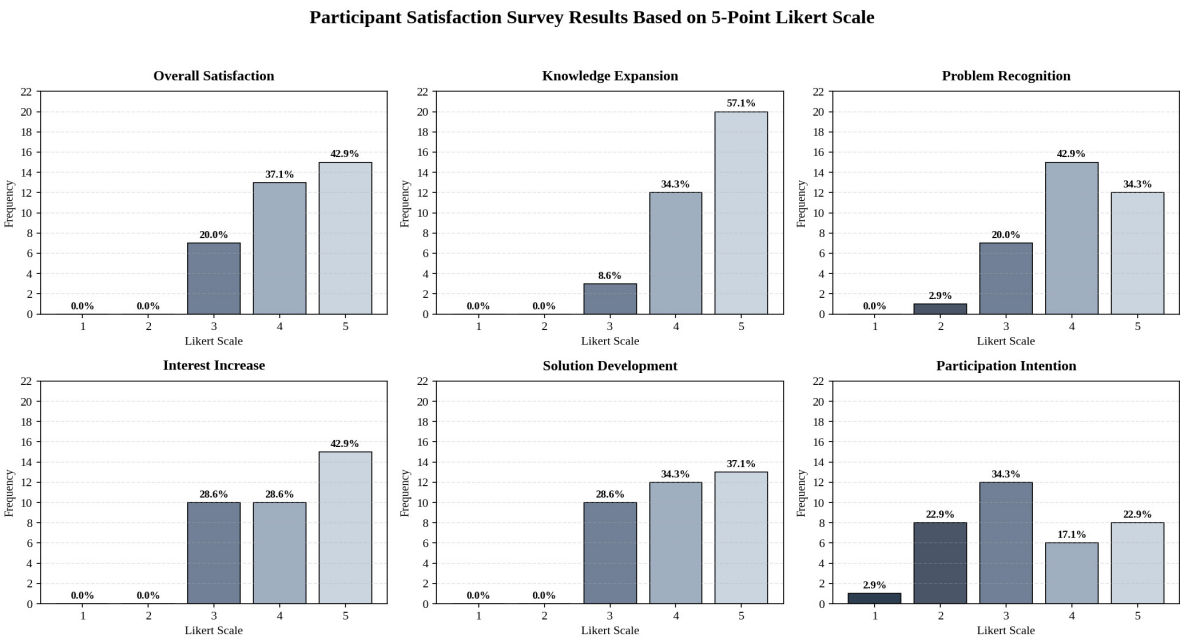
Table 4*Participant Satisfaction Questionnaire Responses (N = 35)*

Item	<i>M</i>	<i>SD</i>
Overall satisfaction	4.23	0.77
Knowledge expansion	4.49	0.66
Problem recognition	4.09	0.82
Interest increase	4.14	0.85
Solution development	4.09	0.82
Future participation intention	3.34	1.16

Five constructs receive positive ratings ($M \geq 4.0$), with the exception of future participation intention. This construct has the lowest mean ($M = 3.34$) and the highest standard deviation ($SD = 1.16$).



Figure 3
Distribution of Satisfaction Questionnaire Responses (N = 35)



The response distribution (Figure 3) shows that knowledge expansion receives the most positive responses, with 91.4% of participants selecting 4 or 5, followed by overall satisfaction (80.0%). Problem recognition (77.2%) and solution development (71.4%) also receive favorable responses. In contrast, future participation intention displays a lower positive response rate (40.0%).

Beyond questionnaire responses, participants’ civic competencies were further examined through qualitative analysis of group activity artifacts. As shown in Table 5, participants identify issues across all five analytical perspectives, though identification rates vary considerably. Health and safety risks (86.8%) and fairness violations (76.3%) show the highest identification rates. In contrast, external coercion (39.5%) and technological impact (36.8%) are less frequently recognized.

Table 5
Problem Identification Across the ELSCI Analytical Perspectives (N = 38)

Analytical Perspective	n (%)	Representative Response Examples
Health and safety risks	33 (86.8)	The technology may have adverse effects on the brains of adolescents during their growth period; While no short-term side effects of tDCS have been identified, long-term use seems risky given that the brain's operating mechanisms are not yet fully understood.
Fairness violation	29 (76.3)	Only those with financial means can purchase the device, creating inequality from the starting line.
Imitation effect	18 (47.4)	If a famous person known for intellectual work uses brain doping, many people will imitate and use it as well.
External coercion	15 (39.5)	Parents obsessed with grades may force their children to use brain doping from an early age, leading to increased dependency on the technology.
Technological influence	14 (36.8)	Unlike drug doping, tDCS use cannot be verified through testing, making regulation difficult.



Solution proposals from Activity E are classified into four categories: regulatory and institutional frameworks, technological safety measures, social equity measures, and educational approaches (Table 6). All groups proposed regulatory solutions (100%), followed by technological safety measures (75%). Educational approaches (50%) and social equity measures (37.5%) were less frequent. Thus, while solutions spanned all four domains, regulatory and technological approaches predominated.

Table 6

Proposed Solutions for Brain Doping (N = 8 Groups)

Solution Category	n (%)	Representative Proposal
Regulatory and institutional frameworks	8 (100.0)	Regulate all those who develop, use, or conceal brain doping technology with 4 years imprisonment and disqualification of athlete status (based on Olympic doping-related laws); Form a committee composed of brain doping-related scientists, existing doping experts, and legal experts
Technological safety measures	6 (75.0)	Conduct preliminary testing to study side effects; Develop personalized tDCS devices to account for individual differences; Create detection equipment to measure abnormal electrical currents in the brain
Social equity measures	3 (37.5)	Establish government-supported booths to increase technology access for low-income groups; Restrict use by minors and elderly to protect vulnerable age groups
Educational approaches	4 (50.0)	Require promotional materials to attach research papers and disclose both positive and negative aspects; Introduce reporting systems to raise public awareness

Discussion

Patterns in Civic Competency Development

The variation in problem identification rates shown in Table 5 may be understood in terms of personal relevance. While participants identified issues across all five analytical perspectives, health and safety risks received the highest identification rate (86.8%), reflecting concerns that directly affect participants' own bodies. Fairness violations (76.3%) were closely associated with participants' immediate experiences of academic competition. Participants frequently referenced the College Scholastic Ability Test and existing socioeconomic disparities. One participant mentioned, "even in current society, economic differences significantly affect academic performance; if technology that grants abilities is introduced, polarization will intensify further."

The analysis of proposed solutions reveals a strong preference for government-led approaches. Table 6 shows that all groups proposed regulatory and institutional frameworks (100%), followed by technological safety measures (75%), educational approaches (50%), and social equity measures (37.5%). Participants consistently positioned the government as the primary actor responsible for addressing brain doping. Specific proposals included legal prohibitions, licensing systems, and publicly funded support programs. For example, one group proposed that "all those who develop, use, or conceal brain doping technology should be regulated with 4 years imprisonment and disqualification of athlete status, based on Olympic doping-related laws." Another group suggested that the government establish government-subsidized public access points to provide tDCS to economically disadvantaged populations.

The qualitative analysis indicates that participants developed civic competencies. First, they exhibited moral sensitivity, defined as the ability to identify the moral aspects of a situation and anticipate consequences for others (Fowler et al., 2009). They recognized multiple dimensions of the brain doping issue and considered impacts on vulnerable populations such as adolescents, economically disadvantaged groups, and those with limited information access. Second, participants acknowledged scientific uncertainty. One participant, for instance, noted that "while no short-term side effects of tDCS have been identified, long-term use seems risky given that the brain's mechanisms are not yet fully understood." This observation aligns with the analysis that tDCS has reached "market entry without restriction" despite lacking rigorous scientific evidence regarding its long-term efficacy and mechanisms (Choi et al., 2025). The ability to understand such epistemic limitations constitutes a critical component of



SSI education (Levinson, 2006). Third, some groups demonstrated the capacity to anticipate consequences and refine their proposals. For example, one group initially proposed age restrictions on tDCS use, and then considered accountability issues arising from side effects that might occur despite warnings. This deliberation led them to propose establishing specialist panels to adjudicate responsibility. Participants also recognized the need for multidisciplinary governance, proposing committees comprising “brain doping scientists, existing doping experts, and legal experts.”

However, certain dimensions remained underdeveloped. Participants gave limited attention to individual autonomy, civil society participation, and international coordination mechanisms. Future program iterations could introduce governance models beyond state-centered approaches and provide opportunities to engage with diverse stakeholder perspectives. Such modifications would strengthen participants’ understanding of participatory governance.

Influences on Future Participation Intention

Participants reported relatively low future participation intention ($M = 3.34$) compared to other questionnaire items. Two interrelated factors may explain this pattern. Regarding program design, Lee (2022) distinguished between citizenship and activism orientations in SSI teaching. Citizenship orientation develops critical perspectives and skills for discourse participation, while activism orientation encourages active problem-solving and direct engagement. The brain doping program emphasized analytical competencies consistent with citizenship orientation, with less emphasis on activism orientation.

The program’s design choice appears to have shaped how participants conceived their roles in technology governance. As the analysis of proposed solutions indicates, participants’ strong preference for government-led approaches suggests that they viewed themselves as recipients rather than active contributors to governance processes. While participants developed awareness of governance mechanisms, they did not fully internalize a sense of agency within those structures.

The gap between awareness and agency can be understood through the lens of Vision III of scientific literacy, which emphasizes preparing students for sociopolitical action as agents of change (Sjöström, 2025; Valladares, 2021). Valladares (2021) argued that transformative scientific literacy requires more than traditional engagement; it calls for an emancipatory approach that broadens participation to include citizens as active contributors to transforming social structures. Sjöström (2025) offered a similar perspective, proposing that such literacy depends on cultivating sociopolitical action competence and agency. From this perspective, the participants’ recognition of issues across ELSCI dimensions and their multi-domain solution proposals represent cognitive foundations of transformative scientific literacy. However, the relatively low future participation intention score indicated that the behavioral dimension remained underdeveloped. These findings suggest that the program’s citizenship-oriented design, while effective in developing analytical competencies, was insufficient to cultivate the agency beliefs necessary for full realization of Vision III.

The broader neurotechnology ELSCI research project, of which this study is a part, included public hearings to incorporate citizen perspectives into policy deliberations (Choi et al., 2025; Jwa et al., 2023). Connecting educational programs to such authentic participatory opportunities may bridge this gap by enhancing learners’ sense of agency and strengthening their intention to engage in technology governance.

Limitations

The first set of limitations concerns research design and measurement. The single-group design limited causal claims attributing observed outcomes to the brain doping program. The self-reported satisfaction questionnaire may have been subject to social desirability bias. Because measurements were taken immediately after the program, the persistence of learning effects was not verified.

The second limitation concerns institutional dependency. This study was conducted within a neuroethics infrastructure at the Korea Brain Research Institute, which provided access to a multidisciplinary expert network and collaborative mechanisms (Jeong et al., 2019; Kang et al., 2023). The availability of such institutional resources may have facilitated the coordination among platforms. Such coordination processes may not generalize directly to settings without established interdisciplinary networks.



Conclusions and Implications

This study proposed MCD as a methodological framework for addressing the distributed expertise challenge in SSI education on emerging technologies and applied it to the development of an SSI-based neuroethics education program on brain doping through tDCS. The three MCD principles—distributed expertise recognition, dialogic knowledge integration, and boundary artifact facilitation—enabled the neuroethics, neuroscience, and public engagement platforms to function as collaborative partners, with brokers and boundary artifacts serving as connecting mechanisms. University students in the pilot implementation identified problems across ELSCI dimensions and proposed solutions spanning regulatory, technological, educational, and social equity domains, indicating the development of civic competencies.

These findings carry implications for multiple stakeholders. For science teachers and teacher educators, this study suggests a shift from a deficit model of teacher competency toward a systemic support model. Given the rapid evolution of neurotechnology, it may be unreasonable to expect individual teachers to master neuroscience, ethical reasoning, and pedagogical design simultaneously. MCD offers a model in which teachers contribute pedagogical expertise to collaborative knowledge construction with domain specialists. For curriculum developers, boundary artifacts and brokers appear essential for interdisciplinary collaboration. The XYZ-axis matrix and ELSCI scaffolding tool enabled communication between neuroscientists, ethicists, and educators by anchoring abstract ethical issues in concrete educational activities. Future projects may benefit from developing such artifacts and identifying brokers to coordinate knowledge integration. For policymakers, SSI-based programs can prepare citizens for participation in technology governance. Policy initiatives need to consider mandating educational components within large-scale research projects and supporting brokers who connect research institutions with schools.

Future research could examine the applicability of MCD across diverse student populations and educational settings, investigate the long-term impacts of SSI-based neuroethics education on civic participation, and extend the framework to other emerging technologies such as artificial intelligence, synthetic biology, and robotics. As emerging technologies increasingly raise complex societal questions, corresponding educational approaches warrant continued development. This study offers MCD as one promising pathway for preparing citizens to navigate the complex ethical landscape of emerging technologies, transforming the challenge of distributed expertise from an obstacle into an educational resource.

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Declaration of Interest

The authors declare no competing interest.

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