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Multisensory Haptic-Audio Didactical Design to Support a Visually Impaired Student's Mastery of Functional Plant Concepts

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Abstract:
Visually impaired students have limited access to visual information, which can hinder their understanding of concepts that are difficult to represent through verbal explanations alone. In IPAS learning, this challenge is particularly evident in understanding the functional relationships among plant parts. Although previous studies have reported the potential of tactile and auditory media, research that uses learning obstacles as the basis for developing didactical designs to guide students' learning trajectories remains limited. This study aims to develop a haptic-audio-based didactical design to address learning obstacles in understanding the functional concepts of plants. The study employed a descriptive qualitative approach using the Didactical Design Research (DDR) method. The participant was a sixth-grade visually impaired student at SKh Negeri 01 Serang City. Data were collected through an initial diagnostic test, classroom observations, teacher interviews, field notes, and a final concept mastery test. Data were analyzed through prospective, metapedadidactical, and retrospective stages. The findings indicate that the main learning obstacle was not the recognition of plant structures through tactile exploration, but the difficulty in connecting these structures with their biological functions. The developed haptic-audio media consisted of a tactile plant model representing the root, stem, branch, and leaf, integrated with audio information describing the biological functions of each plant part. Its implementation, supported by repeated tactile exploration and teacher prompting, helped the student gradually develop an understanding of structure-function relationships. Retrospective analysis resulted in an empirical didactical design that integrates multisensory experiences with adaptive pedagogical support. This study contributes a learning trajectory-based design for more accessible IPAS learning and provides practical guidance for integrating haptic-audio media into inclusive instruction.

Introduction (مقدمة)

Students with visual impairments face barriers in accessing information that is predominantly presented through visual representations in science learning. These barriers become particularly relevant when students are expected to understand structures, spatial relationships, and scientific phenomena that are commonly represented through images, diagrams, or direct visual observation. For this reason, science instruction for visually impaired students requires adaptations that provide meaningful alternatives to visual information. Recent research similarly emphasizes that science and mathematics learning may remain less accessible to students with visual impairments when instructional materials rely heavily on visual representations, highlighting the importance of hands-on experiences, instructional adaptations, and accessible multimodal resources (Hayes & Proulx, 2024; Doore et al., 2023). A review of research on science learning for students with visual impairments indicates that these students can engage successfully with science concepts when appropriate instructional supports are provided, including tactile and kinesthetic experiences, auditory learning, accommodations, and assistive technologies (Ediyanto & Kawai, 2019). Research has shown that appropriately designed hands-on activities and instructional materials can improve access to science learning for students with visual impairments, particularly when the materials are adapted to their perceptual and learning needs (Kızılaslan et al., 2021; Teke & Sozbilir, 2019; Akarsu et al., 2021). for example, Akarsu et al. (2021) demonstrated the use of a tactile-based STEM activity designed to provide students with visual impairment with direct access to scientific concepts through hands-on exploration. However, access to the physical representation of a scientific object does not necessarily ensure that students can establish meaningful relationships between its structure and function. This issue is particularly relevant in elementary science learning, where understanding biological structures requires students to move beyond identifying physical characteristics toward understanding their functional relationships.

Various studies have explored tactile and auditory approaches to improve access to science learning for students with visual impairments. Tactile instructional materials, including two-dimensional and three-dimensional representations, have been developed to help blind students explore scientific structures that are difficult to access through conventional visual representations (Teke & Sozbilir, 2019). Auditory and sonified representations have also been investigated as alternative ways of providing access to scientific information for learners who are blind (Lahav et al., 2018). More recently, audio-tactile media have been reported as a potential approach for supporting science learning among visually impaired students in inclusive classrooms(Sofiana et al., 2025). These studies demonstrate the value of providing multisensory access to scientific information. Recent work has further expanded this approach by integrating haptic and auditory modalities within multisensory learning environments for visually impaired learners. Chit et al. (2024), for example, developed a multisensory learning framework incorporating 3D, haptic, audio, and olfactory media and reported positive usability outcomes among visually impaired participants. Similarly, multimodal systems combining haptic and auditory information have been explored to provide accessible representations of spatial and graphical information in STEM learning (Doore et al., 2023). However, previous research has paid less attention to how students' learning obstacles can be used as a basis for developing a structured didactical design that anticipates possible student responses and guides their learning trajectory.

Addressing this limitation requires an instructional design process that begins by examining how students develop an understanding of a concept and where difficulties emerge throughout the learning process. Within the Didactical Design Research (DDR) framework, identifying learning obstacles provides a basis for formulating didactical situations, anticipating possible student responses, and refining the design through retrospective analysis (Dharma et al., 2021; Pauji et al., 2023; Hendriyanto et al., 2024). In this process, the Hypothetical Learning Trajectory (HLT) can be used to organize the expected development of students' understanding, while the Anticipation of Didactical and Pedagogical (ADP) specifies possible student responses and corresponding teacher interventions. Recent studies employing the DDR approach have further highlighted the importance of examining learning obstacles to understand how students construct and develop conceptual knowledge during instruction. This perspective is particularly relevant to the present study, as the identified difficulty was not associated with recognizing plant structures, but rather with establishing conceptual connections between those structures and their biological functions. Therefore, distinguishing students' ability to recognize a scientific structure from their ability to explain its function is essential for determining an appropriate didactical intervention. In plant science, for example, students may be able to identify roots, stems, branches, and leaves through tactile exploration while still encountering difficulties in explaining their biological functions and relationships. A didactical design grounded in these learning obstacles can therefore integrate tactile exploration, auditory information, learning trajectories, and teacher interventions as interconnected components of the learning situation.

Although tactile, auditory, audio-tactile, and multisensory media have shown potential to enhance learning accessibility for visually impaired students, an important research gap remains concerning how such media are integrated into a didactical design that is explicitly grounded in students' learning obstacles. Previous studies have demonstrated the value of tactile materials, auditory representations, and multisensory interfaces for providing access to scientific and spatial information (Lahav et al., 2018; Chit et al., 2024; Doore et al., 2023). However, these studies have primarily focused on the accessibility, usability, or instructional potential of the media rather than on how students' conceptual difficulties are identified and subsequently used to organize a learning trajectory. In particular, limited attention has been given to the process of connecting an identified learning obstacle with anticipated student responses, teacher interventions, and subsequent refinement of the learning situation. This distinction is important because providing access to a physical or multisensory representation does not necessarily ensure that students can construct the intended conceptual relationships. The present study therefore addresses a didactical gap by integrating a haptic-audio medium into a Didactical Design Research process in which the learning obstacle becomes the basis for constructing the Hypothetical Learning Trajectory (HLT), developing the Anticipation of Didactical and Pedagogical (ADP), implementing the design, and refining it through retrospective analysis. Accordingly, this study aims to develop and examine the implementation of a multisensory haptic-audio didactical design to support a visually impaired student's understanding of functional plant concepts. Specifically, the study identifies the student's learning obstacles in understanding the relationships between plant structures and their biological functions, develops an HLT and corresponding ADP based on these obstacles, and analyzes the implementation by comparing anticipated and actual student responses. The retrospective analysis is then used to refine the hypothetical design into an empirical didactical design that integrates multisensory learning experiences with adaptive pedagogical support.

Method (منهج)

Research design

This study employed a descriptive qualitative approach using Didactical Design Research

(DDR). The use of DDR was considered appropriate because the study aimed not only to describe students' learning difficulties but also to develop, implement, and refine a didactical design based on the learning obstacles identified. The research was conducted through three interconnected stages: prospective analysis, metapedadidactical analysis, and retrospective analysis. The prospective analysis focused on identifying learning obstacles and developing a hypothetical didactical design comprising a Hypothetical Learning Trajectory (HLT), predicted student responses, and Anticipation of Didactical and Pedagogical (ADP). The metapedadidactical analysis examined the implementation of the proposed design and the student's actual responses throughout the learning process. The retrospective analysis linked the initial design with findings from the implementation and the final concept mastery test to identify aspects requiring refinement and to formulate the empirical didactical design. This three-stage structure is consistent with the application of DDR reported in previous studies.

Participant and research setting

The participant was a sixth-grade student with visual impairment at SKh Negeri 01 Kota Serang, Indonesia. The participant was purposively selected based on the relevance of the learning context to the research objectives, particularly the student's involvement in IPAS learning and the need to examine their understanding of functional plant concepts. The study focused on the participant's ability to identify plant structures and explain the biological functions of roots, stems, branches, and leaves. The participant's responses during the diagnostic assessment and classroom implementation constituted the primary unit of analysis. The teacher involved in the learning process also served as an informant through an interview addressing the student's previous learning experiences and difficulties in understanding plant concepts. Given that the study involved a single participant and adopted a qualitative DDR approach, the findings were intended to support the refinement of the didactical design rather than provide statistical generalization to visually impaired students more broadly.

Research Instruments

Data were collected using several instruments aligned with the stages of the DDR process. These instruments included an initial diagnostic test, teacher interview guidelines, observation sheets and field notes, a Hypothetical Learning Trajectory (HLT) and Anticipation of Didactical and Pedagogical (ADP) framework, expert validation sheets for the haptic-audio media and accompanying learning materials, and a final concept mastery test. The initial diagnostic test, teacher interview, and initial observation were employed during the prospective analysis to examine the participant's initial understanding, learning characteristics, and learning obstacles. Findings from these sources were used to develop the HLT and ADP framework, which guided the formulation of the hypothetical learning trajectory and the anticipation of possible student responses during implementation. During the metapedadidactical analysis, observation sheets and field notes were used to document the participant's actual responses and the teacher's pedagogical responses. The final concept mastery test was administered after implementation and analyzed retrospectively using the same indicators and items as the diagnostic test to examine changes in the participant's understanding.

Prior to implementation, the haptic-audio media and accompanying learning materials were evaluated through expert judgment by three validators with relevant expertise: a special education lecturer, a biology lecturer, and a special education teacher. The validation employed a four-point rating scale and assessed the suitability of the media and learning materials in relation to the intended learning objectives and the learning obstacles identified during the prospective analysis. Feedback and comments provided by the validators were considered in refining the media and learning materials before classroom implementation. The instruments and their respective functions across the stages of the DDR process are summarized in Table 1.

Table 1. Research Instruments and Data Sources Across DDR Stages

DDR Stage	Instrumen	Purpose
Prospective Analysis	Diagnostic test for learning difficulties	Identifying students' initial learning barriers Subject matter experts and media specialists
	Observation sheet	Observing student activities and responses during instruction Instructors and Teachers
	Teacher interview	Identifying learning conditions and barriers experienced by students Instructors and Teachers
	HLT and ADP framework	Formulate hypothetical learning trajectory and pedagogical anticipation
Metapedadidactical Analysis	Subject matter expert validation	Assessing the alignment of media content with learning objectives Subject Matter Experts
	Media expert validation	Assessing the suitability of haptic-audio media design Media Experts
	HLT and ADP framework	Compare predicted and actual responses
Retrospective Analysis	Final concept mastery test	Identifying changes in conceptual mastery following design implementation Subject Matter Experts and Media Experts

Research Procedure

The research procedure was carried out through three interconnected stages of Didactical Design Research (DDR).

Prospective Analysis

The prospective analysis was conducted prior to the implementation of the didactical design. This stage began with an examination of the participant's learning condition through teacher interviews, classroom observations, and an initial diagnostic test addressing plant structures and their biological functions. The participant's responses to the diagnostic test were analyzed to identify the learning obstacles encountered, particularly the difficulty in relating tactilely recognized structures to their corresponding biological functions. The findings from this analysis served as the basis for formulating the learning trajectory, predicting possible student responses, and developing the corresponding ADP.

Based on the identified learning obstacles, a hypothetical learning trajectory was formulated to guide the learning process from recognizing plant structures to understanding the functional relationships among those structures. The trajectory involved sequential exploration of the root, stem, branch, and leaf. At each stage, possible student responses were anticipated and corresponding pedagogical responses were prepared. These responses included repeated tactile exploration, repetition of audio explanations, prompting questions, and the use of concrete analogies when conceptual difficulties emerged. The haptic-audio media was then incorporated into the didactical design to establish a connection between tactile exploration and auditory explanations.

Prior to implementation, the haptic-audio media and accompanying learning materials were reviewed by experts to assess their suitability for the intended learning context. The validation involved experts with relevant expertise in special education and biology. Feedback obtained during the validation process was used to refine the media and instructional materials before their implementation in the learning activities.

Metapedadidactical Analysis

The metapedadidactical analysis was conducted during the implementation of the hypothetical didactical design with subject "D". The implementation followed the learning trajectory developed during the prospective analysis, beginning with an orientation to the haptic-audio media and proceeding through sequential tactile exploration of the root, stem, branch, and leaf. Throughout each learning activity, the student's actual responses, difficulties, patterns of exploration, and verbal explanations were documented through direct observation and field notes.

The teacher applied the planned ADP when the student's actual response differed from the predicted response. For instance, when the student was unable to explain the function of a plant structure after listening to the initial audio explanation, the teacher provided a prompting question, encouraged the student to repeat the tactile exploration, or replayed the relevant audio narration. These adjustments were documented as part of the interaction among the didactical design, the student, and the teacher. This stage aimed to examine the relationship between the predicted learning trajectory and the actual learning trajectory that developed during implementation.

Retrospective Analysis

The retrospective analysis was conducted after implementation by relating the findings from the prospective analysis to the actual responses observed during the metapedadidactical stage. The analysis involved comparing the predicted student responses and planned ADP with the responses and pedagogical interventions that occurred during the actual learning process. The final concept mastery test was also examined to identify changes in the participant's understanding of plant structures and their biological functions.

The retrospective analysis was used to determine which components of the hypothetical didactical design were consistent with the student's actual learning trajectory and which required further refinement. Particular attention was given to learning stages in which the student required repeated tactile exploration, repeated audio narration, prompting questions, or concrete analogies. These findings were subsequently used to revise the sequence of learning activities and the timing and form of pedagogical anticipation. The resulting revision constituted the empirical didactical design developed from the implementation and reflection on the hypothetical design.

Data Analysis

The data were analyzed qualitatively based on the three stages of Didactical Design Research (DDR): prospective analysis, metapedidactical analysis, and retrospective analysis. During the prospective stage, data obtained from the initial diagnostic test, teacher interview, and observation were examined to identify the participant's initial understanding and learning obstacles related to the functional concepts of plant structures. The findings from this stage were subsequently used to develop the Hypothetical Learning Trajectory (HLT), formulate predicted student responses, and establish the Anticipation of Didactical and Pedagogical (ADP).

During the metapedidactical stage, observation data and field notes were examined to identify the participant's actual responses during the implementation and the teacher's pedagogical responses to the conditions that emerged. The learning process was analyzed by relating the actual responses to the predicted responses and ADP formulated within the HLT. Particular attention was given to changes in the participant's exploration patterns, conceptual understanding, learning difficulties, and the forms of pedagogical support provided when the actual responses differed from those initially predicted.

In the retrospective stage, findings from the prospective and metapedidactical analyses were compared and interpreted alongside the results of the final concept mastery test. The analysis focused on similarities and differences between the predicted and actual learning trajectories, changes in the participant's understanding of plant structures and their functions, and learning obstacles that persisted following implementation. The results of this comparison were then used to determine which components of the hypothetical didactical design should be retained, modified, or further refined in developing the empirical didactical design.

Result (نتائج)

This study produced findings regarding changes in the understanding of the concept of visually impaired students during the implementation of haptic-audio-based didactical design. The findings were presented following the stages of Didactical Design Research (DDR), namely prospective analysis, metapedadidactical analysis, and retrospective analysis (Suryadi, 2019)

Prospective Analysis

The prospective analysis was conducted to examine the participant's initial conceptual understanding and identify learning obstacles prior to the implementation of the didactical design. Data obtained from the teacher interview, initial observation, and diagnostic test indicated that the participant was able to identify the main parts of a plant through tactile exploration, namely the root, stem, branch, and leaf. Nevertheless, this ability was not yet accompanied by a sufficient understanding of the biological functions associated with each structure. The participant's responses tended to focus on recognizing or describing the physical characteristics of plant parts rather than explaining their respective biological functions. Therefore, the diagnostic test was administered to further examine the distinction between the participant's ability to identify plant structures and the ability to explain the functions of those structures.

Table 2. Subject "D"'s Responses on the Initial Diagnostic Test

Aspect	Subject Response	Interpretation
Identify the roots	Able to identify independently by touch	No obstacles were found in structural identification

Identify the stem	Able to identify the shape of a stem	No obstacles were found in structural identification
Identify the branches	Able to distinguish a twig from a stem	Haptic exploration is progressing well
Identify the leaves	Able to identify leaves by their flat shape	Object identification is proceeding well
Explain the function of the roots	Unable to explain the function of water absorption	Epistemological obstacles
Explain the function of the stem	Does not yet understand the function of water transport	Epistemological obstacles
Explain the function of the branches	Considers it merely a branch of a tree	Understanding is still partial
Explain the function of the leaves	Does not yet understand the process of food formation	Epistemological obstacles

The diagnostic responses revealed a distinct gap between the participant's ability to identify plant structures and their understanding of the functions associated with those structures. Through tactile exploration, the participant was able to recognize the main parts of the plant; however, the ability to describe their biological functions was still limited. For instance, although the participant could identify the root through tactile exploration, the participant was initially unable to explain its role in absorbing water. Comparable difficulties were also found when the participant was asked to explain the functions of the stem, branch, and leaf. These findings suggest that the primary learning obstacle did not stem from difficulties in tactually recognizing plant structures, but rather from the participant's difficulty in establishing connections between the identified structures and their corresponding biological functions.

The interview and observation findings provided further contextual insight into this condition. According to the teacher, the functions of plant structures had previously been taught mainly through verbal explanations, with limited opportunities for the participant to relate tactile experiences to scientific concepts. At the same time, the diagnostic responses showed that the participant had already acquired basic knowledge of plant structures but had not yet established a conceptual connection between each structure and its corresponding biological function. Accordingly, the learning obstacle was primarily interpreted as an epistemological obstacle, in which the participant's existing knowledge of plant structures had not yet been developed into an understanding of the functional relationships among those structures within the plant system. This interpretation subsequently served as an important consideration in determining the direction and development of the didactical design.

Based on the identified learning obstacle, the Hypothetical Learning Trajectory (HLT) was formulated to gradually guide the participant from identifying plant structures through tactile exploration toward understanding their biological functions and the relationships among those functions. The learning trajectory was arranged through a sequential exploration of the root, stem, branch, and leaf, with predicted student responses and corresponding Anticipation of Didactical and Pedagogical (ADP) prepared for each stage. The ADP was designed to support appropriate pedagogical intervention when the participant experienced difficulties or demonstrated responses that did not correspond to the expected learning trajectory. The haptic-audio media was integrated into the didactical situation to establish a connection between the participant's tactile exploration of plant structures and auditory information explaining their biological functions.

Table 3. Hypothetical Learning Trajectory (HLT)

Learning Trajectory	Predicted Student Responses	ADP

Identifying plant parts by touch	Student are able to identify roots, stems, leaves, and branches	The teacher provides guidance on the exploration if student have difficulty identifying the position of objects
Matching roots with their functions	Student only name the roots without knowing their function	The audio explains the function of roots; the teacher provides simple prompts
Matching stems with their functions	Student view the stem as merely a support structure	The teacher guides students to repeat the exploration while listening to the narration
Matching leaves with their functions	Student do not yet understand photosynthesis	The teacher uses the "plant kitchen" analogy after the audio is played
Explaining the relationships among plant parts	Student explain each part separately	The teacher asks students to describe the flow of water from the roots to the leaves

Multisensory Haptic-Audio Didactical Design Learning Media

Prior to the implementation of the didactical design, the haptic-audio media and its accompanying learning materials were reviewed by three validators with relevant areas of expertise, comprising a special education lecturer, a biology lecturer, and a special education teacher. The validation was carried out after the learning obstacles had been identified and the Hypothetical Learning Trajectory (HLT) had been formulated. This sequence allowed the media and learning materials to be evaluated based on the specific learning needs identified during the prospective analysis. A four-point rating scale was used to assess the appropriateness of the media and learning materials in relation to the intended learning objectives and the identified learning obstacles.

The haptic-audio media received a total validation score of 183 from a maximum possible score of 204, corresponding to 89.71%. Meanwhile, the learning materials obtained a score of 128 out of a maximum of 156, equivalent to 82.05%. The overall validation score was 311 out of 360, or 86.39%. These findings indicate that both the haptic-audio media and the accompanying learning materials fulfilled the criteria specified in the expert assessment and were deemed appropriate for implementation. In addition to the quantitative scores, feedback and recommendations provided by the validators were taken into consideration to further refine the media and learning materials before they were implemented in the learning activities.

Figure 1. Haptic-audio plant model used in the didactical design.

Figure 1 illustrates the haptic-audio plant model employed during the implementation of the didactical design. The model represents the main plant structures explored by the participant, including the root, stem, branch, and leaf, with tactile exploration combined with corresponding audio information explaining the biological functions of each structure.

Metapedadidactical Analysis

The metapedadidactical analysis was conducted to examine the implementation of the haptic-audio-based didactical design developed during the prospective analysis. The analysis focused on the correspondence between the Hypothetical Learning Trajectory (HLT), the predicted student responses, and the actual responses that emerged throughout the learning process. Data were obtained through direct observation and field notes, enabling the researcher to examine how the Anticipation of Didactical and Pedagogical (ADP) framework developed during the prospective stage was implemented in response to the participant's actual learning conditions (Suryadi, 2019).

The learning process began with an orientation activity using the haptic-audio media. The teacher provided subject "D" with an opportunity to explore the three-dimensional plant model using both hands before the audio narration was activated. This initial activity was intended to support the development of a spatial representation of the location of each plant structure, allowing the participant to focus on tactile exploration without having to simultaneously process verbal information. During this orientation stage, the participant was able to identify and develop an initial spatial representation of the root, stem, branch, and leaf. This allowed the participant to become familiar with the overall structure of the model before receiving the corresponding audio information and to independently explore each plant part through tactile interaction.

After the orientation phase was completed, the teacher instructed the participant to touch each plant part sequentially according to the designed learning trajectory. Each touch on a specific part triggered an audio narration explaining its biological function. Initial responses indicated that the participant repeatedly touched the same part while listening to the audio explanation again. This pattern suggests that the participant began to connect the information obtained through tactile exploration with the verbal explanations presented simultaneously. Compared with the diagnostic test results, the exploration process during implementation was more systematic, beginning with the root, followed by the stem and branch, and ending with the leaf.

Several responses that had been predicted during the prospective phase were also observed during the learning process. The participant was not yet able to explain the function of the stem after listening to the audio narration for the first time. This finding was consistent with the prediction that the participant might perceive the stem primarily as a supporting structure for the plant. The teacher then implemented the ADP through a prompting question, such as, "If water is absorbed by the roots, through which part do you think the water moves upward?" The participant was subsequently asked to explore the stem again while listening to the audio narration. This repetition helped the participant understand that the stem functions as a pathway for transporting water to other parts of the plant.

A similar response was observed when the participant learned about the function of the leaf. During the first exploration, the participant still had difficulty explaining the biological function of the leaf despite having listened to the audio narration. The teacher then reinforced the concept through a simple analogy, explaining that the leaf is the "kitchen of the plant," where the plant produces food. This explanation was provided after the participant explored the leaf again while listening to the narration for a second time. The repeated multisensory experience helped the participant connect the physical characteristics of the leaf with its biological function, enabling the participant to explain the concept in their own words.

A change in the exploration process was also observed when the participant learned about the relationship among the stem, branch, and leaf. Initially, the participant recognized the branch as a smaller extension of the stem but had not yet understood its relationship with the other plant structures. The teacher then directed the participant to explore the structures sequentially, beginning with the stem, continuing to the branch, and finally reaching the leaf, while providing the prompting question, "After the stem, which part do your hands move to before reaching the leaf?" This approach helped the participant understand that the branch serves as a connection between the stem and the leaf and provides a place where leaves grow. Although the participant's explanation still required some teacher guidance, the finding indicates that pedagogical support was more effective when integrated with direct tactile exploration rather than provided through verbal explanation alone.

Overall, the implementation of the didactical design showed that the interaction among the teacher, participant, and media generally followed the HLT developed during the prospective phase. The haptic-audio media served to connect tactile and auditory information, while the teacher provided ADP when the participant's responses differed from the predicted responses. Most of the conceptual obstacles observed during implementation could be addressed through repeated exploration, prompting questions, and concrete analogies. These findings suggest that the implementation of the didactical design depended not only on the media itself but also on the teacher's pedagogical decisions in responding to the learning conditions that emerged throughout the instructional process.

Table 4. Implementation of Didactical Design, Subject "D"'s Actual Responses, and Anticipation of Didactic and Pedagogical (ADP)

Learning Stages	Subject "D" Actual Response	Didactic and Pedagogical Anticipation (ADP
Media Orientation	Exploring the shape of the media using both hands to identify the shape and position of each part	The teacher provides an opportunity for free exploration before the audio is played so that students can build a spatial representation of the object
Exploring Roots	The student repeatedly touched the root section while listening to the audio	The teacher directs student attention to the relationship between the texture of

Learning Stages	Subject "D" Actual Response	Didactic and Pedagogical Anticipation (ADP
	narration. After receiving a prompting question from the teacher, the subject began to explain that the root functions to absorb water.	the root and the audio information they hear
Exploring Stems	Unable to explain the function of the stem after the first narration was played	The teacher asks a prompt question and asks student to repeat their exploration of the stem while listening to the audio again
Exploring Twigs	Recognizes twigs as small branches but does not yet understand the relationship between twigs and leaves	The teacher guides a sequential exploration from the stem to the twigs and then to the leaves, accompanied by prompt questions to establish connections between concepts
Exploring Leaves	Begins to understand that leaves are where plants produce food but still requires verbal assistance to formulate an explanation.	The teacher uses the "plant kitchen" analogy after student touch the leaves again while listening to the audio narration
End of Lesson	Able to explain the relationship between roots, stems, branches, and leaves in a more coherent manner than before the lesson	The teacher conducts a brief confirmation and reflection to reinforce student conceptual understanding.

Retrospective Analysis

The retrospective analysis phase was conducted by integrating the results of the prospective analysis, the implementation of the didactical design during the metapedadidactical phase, and the results of the final concept mastery test. The analysis focused on comparing the Hypothetical Learning Trajectory (HLT), predicted student responses, and actual responses observed throughout the learning process. This comparison was conducted to identify which components of the design were implemented as initially planned and which required adjustment based on the participant's actual learning conditions. Within the framework of Didactical Design Research (DDR), retrospective analysis serves as a stage for reflecting on the relationship between the hypothetical didactical design and the actual learning process, which subsequently provides a basis for developing an empirical didactical design. In this study, the results of the final concept mastery test were interpreted together with the participant's actual responses during learning to provide a more comprehensive description of the development of conceptual understanding.

A comparison between the HLT and the actual responses showed that the participant was able to follow most of the learning trajectory designed during the prospective phase, although several situations required more specific pedagogical support. During the orientation phase, the prediction that the participant would be able to explore the media independently was confirmed by the conditions observed during implementation. The participant was able to explore the root, stem, branch, and leaf through tactile interaction without direct assistance from the teacher. In the process of connecting the structure of the root with its function, the tactile experience accompanied by audio narration helped the participant understand the relationship between the root and its function in water absorption. A different condition was observed when learning about the function of the stem, as the participant was unable to explain its function after listening to the narration for the first time. The teacher subsequently provided ADP through prompting questions and guided the participant to repeat the exploration while listening to the audio narration again. These findings indicate that the actual learning trajectory did not proceed entirely linearly according to the initial HLT but developed through adjustments based on the participant's responses.

Differences between the predicted and actual responses were also observed during the learning of the branch and leaf functions. The participant was able to identify the branch through tactile exploration but had not yet developed an immediate understanding of the relationship among the branch, stem, and leaf. The teacher therefore guided the participant through sequential exploration, beginning with the stem, continuing to the branch, and then reaching the leaf, while providing prompting questions to support the participant in establishing relationships among these structures. Regarding the function of the leaf, the participant still required repeated explanations and support through the "plant kitchen" analogy to understand that the leaf is involved in the process of food production. This condition indicates that tactile and auditory experiences do not necessarily result in conceptual understanding immediately, particularly when the concept involves a higher level of abstraction. Repeated multisensory experiences and appropriate pedagogical support were therefore important in adapting the learning process to the participant's actual responses. These retrospective findings demonstrate that the actual learning trajectory involved adjustments to the planned trajectory, particularly in developing an understanding of the functional relationships among plant structures.

The development of conceptual mastery was further examined by comparing the results of the diagnostic test with those of the final concept mastery test. Both instruments used the same learning indicators, allowing changes in the participant's understanding of each indicator to be observed directly. The comparison showed that the participant's ability to identify plant structures had already been established at the beginning of the study, whereas more noticeable changes occurred in understanding the biological functions of the respective plant parts. The score for root function increased from 2 to 4, stem function from 1 to 3, branch function from 1 to 3, and leaf function from 1 to 2. This pattern was consistent with the observations during implementation, which indicated that the main development occurred in the participant's ability to connect plant structures with their biological functions rather than in the ability to recognize the plant parts themselves. Therefore, the final concept mastery test served as supporting evidence that strengthened the interpretation of changes in the participant's learning trajectory and conceptual understanding observed during the learning process.

Table 5. Comparison of Conceptual Understanding Before and After the Implementation of the Didactical Design

Indicators	Starting Score	Final Score	***Interpretation of Changes***
Identify roots	*4*	*4*	Still able to identify roots independently.
Identify stems	*4*	*4*	Still able to identify stems independently.
Identify branches	*3*	*4*	Identification skills became more accurate after exploring the medium.
Identify leaves	*4*	*4*	Still able to identify leaves independently.
Explain the function of roots	*2*	*4*	Able to explain the function of roots as water absorbers after gaining multisensory learning experiences.
Explain the function of stems	*1*	*3*	Begins to understand the stem as a pathway for water transport, although still requires a little verbal assistance.

Indicators	Starting Score	Final Score	***Interpretation of Changes***
Explain the function of branches	*1*	*3*	Begins to understand the relationship between branches and the stem, and that leaves grow from the stem.
Explain the function of leaves	*1*	*2*	Begins to understand the function of leaves as sites for food production, but explanations still require the teacher's assistance.

The results presented in Table 5 indicate that the most noticeable changes in conceptual mastery occurred in the indicators related to the biological functions of plant parts. The scores for identifying the root, stem, and leaf remained unchanged because the participant had already been able to recognize these three structures before the didactical design was implemented. The increase in the identification of the branch, from a score of 3 to 4, reflects a modest improvement in the accuracy of tactile structural exploration; however, this change does not represent the main development in conceptual mastery. A more substantial improvement was found in understanding the function of the root, which increased from a score of 2 to 4. Initially, the participant was able to recognize the physical form of the root but could not explain its biological function. Following the implementation, the participant was able to describe the root as the plant structure responsible for absorbing water. Understanding of the functions of the stem and branch also increased from a score of 1 to 3, although the participant still required limited verbal support to formulate the explanations. Meanwhile, understanding of the leaf function increased from a score of 1 to 2, suggesting that the concept had begun to develop but still required further reinforcement in subsequent learning activities.

These findings provided a basis for determining which components of the didactical design should be maintained and which required further refinement. The orientation activity involving tactile exploration before the audio narration was activated was retained because it corresponded to the participant's actual responses and supported the development of an initial spatial representation of the position and arrangement of the plant structures. The integration of tactile exploration and audio narration was also maintained, while repeated exploration was incorporated as an essential component of the learning trajectory when the participant did not fully understand the information after its initial presentation. For the function of the stem, the ADP was strengthened through prompting questions that connected the root's function in absorbing water with the stem's role in transporting water to other parts of the plant. For the branch function, the exploration sequence from the stem to the branch and then to the leaf was clarified to facilitate the participant's understanding of the structural relationships among these parts. For the function of the leaf, the "plant kitchen" analogy was retained as a pedagogical support because it provides a more concrete representation of the process through which plants produce food.

Refinement of the Didactical Design

The retrospective analysis served as the basis for refining the hypothetical didactical design into an empirical didactical design. This refinement was based on an examination of the components that were consistent with the participant's actual responses and those that required modification during the implementation process. The findings indicated that the haptic-audio media and the initial tactile orientation were appropriate for facilitating the participant's exploration of plant structures and were therefore maintained in the empirical design. However, tactile and auditory experiences alone did not always lead to an immediate understanding of biological functions, particularly in relation to the stem, branch, and leaf. Therefore, the empirical design included more explicit opportunities for repeated exploration, prompting questions, and the use of concrete analogies when the participant's responses did not correspond to the expected learning trajectory.

The refinement also involved clarifying the sequence of the learning trajectory. The empirical design retained the progression from identifying plant structures, to understanding the function of each structure, and then to establishing relationships among the functions of different structures. For the stem and branch, the sequence of tactile exploration was further strengthened by guiding the participant from the stem to the branch and leaf while using prompting questions to support the formation of functional relationships. For the leaf, repeated tactile-auditory exploration and the use of the concrete "plant kitchen" analogy were maintained as pedagogical responses because the participant continued to require support in explaining its biological function. Thus, the refinement involved not only the integration of haptic-audio media but also the timing and form of pedagogical interventions within the didactical situation.

The resulting empirical didactical design represents a refinement derived from a single implementation cycle. This result does not indicate that the design has reached a final or universally applicable form. Instead, the empirical design provides an evidence-based refinement of the initial hypothetical design that reflects the participant's actual responses and the pedagogical adjustments required during implementation. Further refinement can be undertaken through subsequent implementation cycles involving different learning situations and participants.

Table 6. Refinement of the Didactical Design Based on Retrospective Analysis

Design Component	Implementation Finding	Empirical Didactical Design
Media orientation	The participant was able to explore the form and position of plant structures independently.	Initial tactile orientation before audio activation was retained.
Root function	The participant understood the root function after tactile exploration accompanied by audio narration.	Tactile-auditory exploration was retained with an opportunity for repetition.
Stem function	The initial audio narration did not sufficiently support the participant in explaining the stem function.	Prompting questions and repeated tactile-auditory exploration were incorporated.
Branch function	The participant recognized the branch but had difficulty relating it to the stem and leaf.	The stem–branch–leaf exploration sequence was clarified and accompanied by prompting questions.
Leaf function	The participant continued to require support to explain the leaf function.	Repeated tactile-auditory exploration and the "plant kitchen" analogy were retained as pedagogical responses.
Relationships among plant structures	Understanding of structure–function relationships began to develop but was not yet fully independent.	An activity connecting the sequence root–stem–branch–leaf was incorporated to strengthen functional relationships.

Table 6 indicates that the refinement mainly involved the organization of the didactical situation and the timing of pedagogical support rather than replacing the haptic-audio media itself. Components that had effectively supported the participant's tactile exploration were retained, while additional prompting, repeated exploration, and explicit connections between plant structures were incorporated when the participant's actual responses differed from the predicted learning trajectory. The empirical design thus represents a refinement of the hypothetical design based on evidence obtained during the implementation process. This refinement further strengthens the learning trajectory by guiding the participant from identifying plant structures toward understanding their biological functions and the functional relationships among different plant structures.

Discussion (مناقشة)

The findings of this study suggest that the primary contribution of the developed didactical design extends beyond providing tactile and auditory access to learning content. More importantly, the design organized these sensory experiences into a learning trajectory that responded to the participant's specific conceptual difficulties. A clear example occurred during the learning of the stem function: after listening to the initial audio narration, the participant was still unable to explain the role of the stem, consistent with the predicted response that the stem might be understood primarily as a supporting structure. The teacher then asked, "If water is absorbed by the roots, through which part do you think the water moves upward?" and asked the participant to explore the stem again while listening to the narration. Following this intervention, the participant began to understand the stem as a pathway for transporting water. A similar pattern occurred for the leaf, where the initial audio explanation did not immediately result in conceptual understanding, and the teacher subsequently used repeated tactile-auditory exploration and the "plant kitchen" analogy to support the participant's explanation. These examples indicate that the learning process did not depend on the media alone, but rather on the interaction among the haptic-audio representation, the participant's responses, and the teacher's adaptive pedagogical actions, consistent with the principles of Didactical Design Research, which emphasize refining learning situations based on actual student responses (Suryadi, 2013).

The integration of tactile and auditory information appeared to support the participant in establishing connections between concrete structural experiences and biological functions, but the process was not immediate for all plant parts. During the learning of the root, the participant repeatedly touched the root section while listening to the audio narration and, after teacher prompting, was able to explain that the root functions in water absorption. In contrast, the first audio narration was insufficient for understanding the stem function, and the participant required a prompting question and repeated exploration while listening to the narration again. The leaf presented an additional challenge because the participant continued to require verbal assistance even after repeated tactile-auditory exploration, leading the teacher to introduce the "plant kitchen" analogy to make the function of the leaf more concrete. These process-level findings are consistent with, Chit et al. (2024),who highlighted the potential of combining haptic and audio modalities in multisensory learning environments for visually impaired learners, but the present study adds evidence concerning how such modalities can be adapted in response to specific conceptual difficulties during instruction. Thus, the contribution of multisensory media in the present case was not simply the simultaneous availability of tactile and auditory information, but its integration with repeated exploration and responsive teacher intervention within a structured learning trajectory.

The findings may also be interpreted through Cognitive Load Theory, particularly the principle that unnecessary demands placed on working memory can interfere with the process of constructing new knowledge (Sweller et al., 2019). Prior to the implementation of the didactical design, the participant obtained information about plant structures through tactile exploration, while information concerning their functions was primarily delivered through verbal explanations. This condition required the participant to establish connections between two sources of information that were not always coordinated within the same learning activity. The haptic-audio design reduced this separation by presenting auditory information while the corresponding plant structure was being explored. Nevertheless, the findings should not be interpreted as direct evidence that the media independently reduced cognitive load, since cognitive load was not directly measured in this study. Instead, Cognitive Load Theory provides a plausible interpretive perspective for explaining why the coordination of tactile exploration and auditory explanation may have supported the participant's conceptual processing. The learning process observed in this study therefore suggests that the pedagogical organization of information may be as important as the sensory characteristics of the instructional medium.

The findings are also consistent with the general principle of complementary verbal and nonverbal representations proposed in Dual Coding Theory (Paivio, 1990). In this study, tactile exploration provided access to nonverbal information concerning the physical characteristics of plant structures, whereas the audio narration conveyed verbal information regarding their biological functions. The combination became meaningful because both forms of information referred to the same learning object and were connected through teacher-guided learning activities. As a result, the participant was not required to independently establish the relationship between the physical object and its verbal description. However, Dual Coding Theory should be regarded as an interpretive framework rather than a causal explanation demonstrated by the present study because cognitive representation and processing were not directly measured. The more direct empirical contribution of this study lies in identifying the participant's learning obstacle and developing a didactical sequence that supported the transition from recognizing plant structures to understanding their biological functions.

The findings are consistent with previous studies showing that tactile and multisensory approaches can improve access to science learning for students with visual impairments, while also differing in how the instructional process was organized. Teke and Sozbilir (2019), for example, demonstrated that 2D and 3D tactile instructional materials could support a blind student in understanding complex scientific concepts when the materials were adapted to the student's needs. Similarly, Akarsu et al. (2021) showed the value of hands-on tactile STEM activities in providing students with visual impairments with direct access to scientific learning. The present study supports these findings because the participant was able to independently recognize plant structures through tactile exploration, but it also demonstrates that tactile access did not automatically result in an understanding of biological functions. This difference became particularly evident in the stem and leaf activities, where the participant required repeated exploration, prompting questions, and a concrete analogy after the initial tactile-audio presentation. In relation to Keleş et al. (2023), who developed plant life-cycle learning activities and materials based on the individual needs of visually impaired students, the present study similarly emphasizes adaptation to learners' needs but extends the process by using an identified learning obstacle to organize the HLT, formulate the ADP, and subsequently refine the learning trajectory. Therefore, the present study contributes not merely another accessible science activity, but a didactical process showing how an accessible medium can be dynamically adjusted according to the learner's actual conceptual responses.

This distinction is particularly relevant to understanding the empirical didactical design produced through the retrospective analysis. The implementation demonstrated that tactile and auditory experiences did not automatically lead to complete conceptual understanding. In several learning situations, the participant required repeated tactile exploration, prompting questions, and concrete analogies before the relationships between plant structures and their functions became more understandable. Consequently, the refinement of the design did not primarily involve replacing the haptic-audio medium, but rather modifying the manner in which the medium was incorporated into the learning situation. The empirical design therefore identifies conditions under which tactile exploration should be repeated, situations in which auditory information should be reinforced through questioning, and circumstances in which the teacher should provide additional conceptual support. This finding further supports the DDR perspective that refinement of a didactical design should be grounded in the relationship between the anticipated learning process and the actual responses that emerge during implementation (Suryadi, 2013). Accordingly, the empirical design should be viewed as a context-sensitive instructional proposition rather than a universally applicable teaching procedure.

The practical implication of these findings is that inclusive science instruction for visually impaired students should treat accessibility, conceptual development, and teacher responsiveness as interconnected components of the learning process. Tactile representations can provide access to the physical characteristics of an object, but learners may still require pedagogical support to interpret those characteristics from a scientific perspective. Likewise, audio information can provide verbal descriptions, but its instructional contribution may be enhanced when it is synchronized with the learner's ongoing exploration of the corresponding object. The findings of this study therefore suggest that haptic-audio media is more appropriately positioned as part of an adaptive didactical design rather than as a standalone instructional product. The study also provides a practical illustration of how identified learning obstacles can be translated into anticipated student responses and pedagogical actions within a learning trajectory. Nevertheless, these findings should be interpreted within the limitations of the study, particularly the involvement of a single sixth-grade visually impaired participant and one implementation cycle. Further research involving more participants, repeated implementation cycles, and different science concepts is needed to examine the transferability of the empirical didactical design and to support its further refinement.

Conclusion (خاتمة)

This study concludes that a haptic-audio didactical design can support visually impaired students in developing an understanding of functional relationships among plant structures through an accessible learning trajectory. The main learning obstacle was not the ability to recognize plant structures through tactile exploration, but the difficulty of relating these structures to their biological functions. This obstacle served as the basis for developing the Hypothetical Learning Trajectory (HLT) and Anticipation of Didactical and Pedagogical (ADP) within the Didactical Design Research framework. The resulting empirical design offers practical guidance for teachers by coordinating tactile exploration, audio information, repeated exploration, and targeted prompts or concrete analogies in response to students' conceptual difficulties. However, as the study involved one sixth-grade visually impaired student and one implementation cycle, its findings cannot be considered statistically generalizable. Further research is therefore needed to refine the design with multiple learners, diverse learning contexts, and additional DDR cycles.

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