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Design-Based Research in Higher Education: Analysing Examples Through Activity Theory and Bakker's five characteristics

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Abstract

This conceptual paper aims to identify the characteristics of Design-Based Research (DBR) projects that support the sustainable, expansive or adaptive implementation of technological learning innovations in higher education and thus address this gap in the literature. Four examples of Design-Based Research implemented in different discipline contexts through technology enhanced learning interventions in higher education are retrospectively analysed and compared. The higher education discipline contexts of the projects include health education, music performance, biomedical engineering, electrical and mechanical engineering. The analysis uses a shared framework based upon identifying five characteristics of design research and activity theory. Shared characteristics include addressing an identified pedagogical problem or innovation through iteratively designing and evaluating an intervention that enhances learning while developing theoretical insights. Transdisciplinary collaboration enhances the transferability of design principles derived from these projects into wider contexts. Activity Theory analysis is utilised to identify context-specific contradictions and strengths in each example. These four longitudinal project designs illustrate how Design-Based Research can be combined with Activity Theory and practically implemented as a transferable educational design framework to generate impact on teaching and learning that is either sustained, expansive or adaptive.

Practitioner Notes

1. Design-Based Research projects embrace the 'messy' elements of learning and teaching to understand real practice.
2. Activity Theory analysis aids the development of theoretical insights of Design-Based Research.
3. Combining Design-Based Research with Activity Theory creates a model enabling projects to navigate the complex impact of rules, community, and division of labour within Activity Theory systems.

Keywords

Design-Based Research, Pedagogical design, Collaborative curriculum design, Technology Enhanced Learning, Activity Theory.

Citation:

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Introduction

The application of Design-Based Research (DBR) to higher education curriculum design, also known as Educational Design Research (EDR) has a long history (Galvin & Cochrane, 2023). The naming of 'design-based research' was proposed in 2002 in line with the Design-Based Research Collective (2003) direction, highlighting that it is educational research first (leading to a knowledge claim) in the context of a design process. McKenney and Reeves (2012) use the term 'educational design research', to help distinguish from a discipline with less of an emphasis on education. Bakker (2018) suggests 'research–based design' best describes when the design is informed by research, in comparison to 'design-based research' for research that is possible due to the existence of a new design, and 'design research' as a combination of the two approaches. We use the term Design-Based Research throughout this paper.

Design-Based Research uses a design approach to solve an identified problem. The problem this paper addresses is the on-going critique of Design-Based Research that there is a lack of examples of implementing Design-Based Research outcomes beyond a specific project to amplify the impact on praxis to be truly transferable (Haagen-Schützenhöfer et al., 2024; Henriksen & Ejsing-Duun, 2022). Kopcha et al., (2015) argue that there is a need for a wider variety of Design-Based Research examples, especially in response to the impact of educational technology in higher education. More recently Jacobsen and McKenney (2024) also argue that more examples are needed of rigorous and fit-for-purpose methods of implementing Design-Based Research particularly within the context of exploring technology enhanced learning (TEL) in higher education (HE). These are needed to develop an understanding of what works in practice that is sustained, expansive or adaptive (Henriksen & Ejsing-Duun, 2022). Therefore, we propose:

> **Research Question 1.** What are the characteristics of Design-Based Research projects utilising technology-enhanced learning innovations in Higher Education that support sustained, expansive or adaptive implementation?

This paper addresses this question by analysing four Design-Based Research project examples to illustrate how combining Design-Based Research with Activity Theory creates a framework that can be implemented and understood to inform sustained real-world pedagogical practice that transforms teaching and learning in a variety of discipline contexts. The retrospective analysis of four example Design-Based Research projects exploring Technology Enhanced Learning to address identified pedagogical problems in four different Higher Education discipline contexts illustrates an implementation and analysis framework that can inform the implementation of Design-Based Research in other (expansive or adaptive) teaching and learning contexts.

Literature

The technology enhanced learning literature is dominated by quasi-experimental case studies (mostly short-term) of technology interventions that exhibit no significant difference in learning outcomes to prior pedagogical practice beyond increasing student engagement (Amiel & Reeves, 2008; Reeves & Lin, 2020; Selwyn, 2015). This is often due to a techno-centric focus in quasi-experimental comparative studies that position a technology-based intervention against prior pedagogical practice rather than addressing the fundamental cause of a pedagogical problem or enabling the development of new pedagogies through innovation. Design-Based Research approaches technology enhanced learning through a design lens in comparison to quasi-experimental approaches to curriculum design that focus upon comparative studies involving a control group and an intervention group. Amiel and Reeves (2008) argue Design-Based Research provides an ethical approach to technology enhanced learning interventions through addressing an identified learning problem (pedagogy-first) rather than being techno-centric (technology-first). However, Design-Based Research is criticised for failing to identify context specific socio-cultural issues that limit wider transferability of identified design principles and a lack of practical implementation examples (Kopcha et al., 2015). Combining Activity Theory with Design-Based Research has been proposed as a solution (Penuel et al., 2016) but there are limited examples of this in practice.

Design-Based Research Characteristics

Bakker (2018, p. 18) outlines five characteristics of Design Research:

1. Its purpose is *to develop theories about learning and the means that are designed to support that learning*.
2. It is *interventionist* in nature.
3. Has *prospective and reflective components* that need not be separated by a trial or so-called teaching experiment.
4. *The cyclic* nature of design research: Invention and revision form an iterative process.
5. The *theory* under development *has to do real work*.

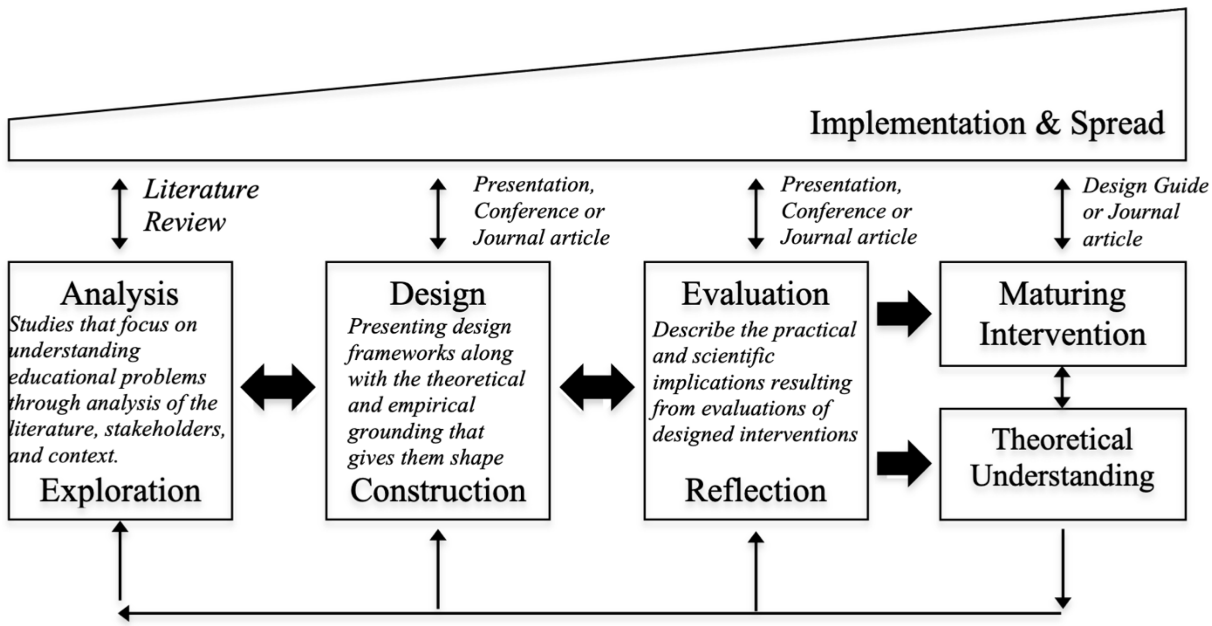
The goal of Design-Based Research is the development of transferable design principles that can be applied in contexts beyond a single specific study. Bakker (2018) characterises design principles as “guidelines, advice, or heuristics – something to consider and try out, with the common sense understanding that no two situations will be identical and that adaptation to local circumstances is always necessary” (Bakker, 2018, p. 52). Design-Based Research projects emulate both ‘naturalistic generalisablity’ by resonating with others when outcomes are familiar to their own settings, and ‘inferential transferability’ when others in different contexts decide to adopt and adapt contributions from other research (Galvin, 2023; Smith, 2018). Design-Based Research offers an opportunity to make theory a lived possibility that is observed in action (Domínguez, 2017). As Abrahamson (2018) explains, there is scope when using Design-Based Research to design artefacts over time that motivates improvement of a central theory lens. Bakker (2018) states that a conclusion on a learning theory may even become a more prominent outcome than the design itself in Design-Based Research. An alternative outcome of Design-Based Research is the development of conjecture maps, that are more common in Scandinavian approaches to Design-Based Research (Sandoval, 2014). Bakker (2018) describes design principles as implicitly hypothetical in nature whereas conjecture maps are explicitly hypothetical and predictive. To help demystify the implementation of Design-Based Research this paper focuses upon the development of design principles rather than conjecture mapping. Simplifying Van den Akker (2013), a statement of design principles has the following format:

> To design intervention X for the purpose of Y in the context of Z (What), the intervention should have these characteristics C through the procedure P (How) to develop the theoretical T and empirical E arguments (Why).

Design-Based Research foundations in the design of higher education can be located in the work of Barab and Squire (2004), Kelly (2003), Sandoval and Bell (2004) and more recently in the work of McKenney and Reeves (2019; 2020). McKenney and Reeves outline four phases or stages of Design-Based Research/Educational Design Research and Kopcha et al., (2015) argue that various outputs from each phase of Design-Based Research can be reported as shown in figure 1.

Figure 1

Phases of Educational Design Research (Modified from (McKenney & Reeves, 2019))



The following sections summarise McKenney and Reeves four phases of Educational Design Research/Design-Based Research aligned to Bakker's 5 characteristics of Design-Based Research.

The first phase of Design-Based Research involves identification of the curriculum design problem or innovation (Bakker's first characteristic), for example – how to design an authentic student-centred project that is scaffolded across a curriculum and the critical issues surrounding the specific learning environments. This is followed by the exploration of supporting literature, often through a scoping or systematic review, to identify initial design principles to address these issues and identify gaps in the literature. This applies theory to a specific context to do real work as identified by Bakker's fifth design research characteristic.

The second phase of Design-Based Research draws upon the design principles identified in the first phase of Design-Based Research and leads to prototyping of the collaborative curriculum design informed by the identified design principles. A design thinking approach can be utilised to guide the design and construction phase (Cochrane & Munn, 2020). Such designs are interventionist by nature according to Bakker's second design research characteristic.

The third phase of Design-Based Research involves evaluation of the prototype curriculum and subsequent collaborative curriculum redesign through user feedback (students and project team peers), and refinement of the design principles. This is Bakker's third characteristic – the prospective (forward looking) and reflective components of design research. This then leads to a design/evaluation phase 2-3 Loop (Characteristic four – the cyclic nature of design research): Iterative redesign and re-evaluation of the collaborative curriculum design or teaching experiment.

The final phase of Design-Based Research leads to development of transferable design principles and dissemination of findings for application to other learning contexts. This is Bakker's primary characteristic of design research – its purpose is to develop theories about learning and the means to support that learning. As a methodological framework, Design-Based Research has a dual focus, to be instrumental, by manipulating the environment, and to observe the naturalistic ways students engage with learning (Bakker, 2018; Galvin, 2023).

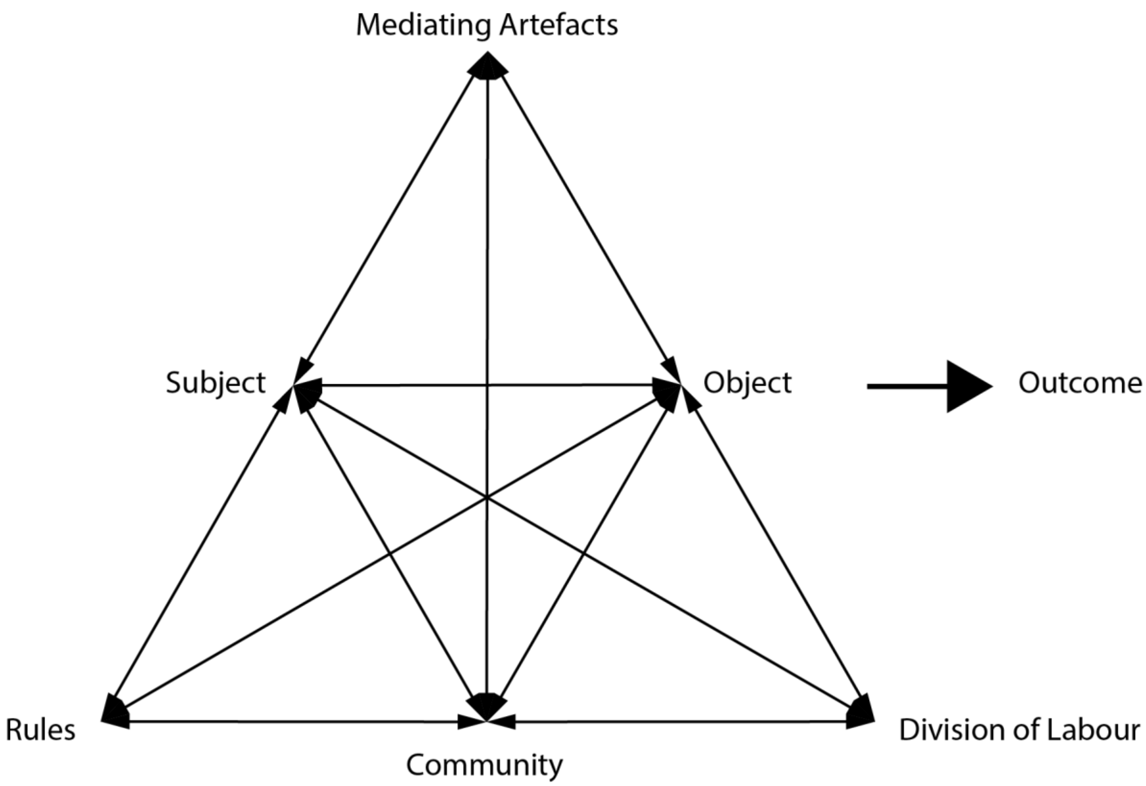
Based upon a scoping review of Design-Based Research case studies Henriksen and Ejsing-Duun (2022) identify a two-dimensional model consisting of four quadrants across two dimensions (axis) of (1) stakeholder and context and (2) timeframe and budget, to illustrate Design-Based Research implementation typologies and strategies that can improve the impact and sustainability of these projects on other learning contexts. These implementation strategies are defined as sustained, expansive, or adaptive. Sustained implementation strategies lead to continued impact on the participants and institutions beyond the end of the project – strategies include nurturing ambassadors or institutionalising findings. Expansive implementation strategies impact stakeholders and contexts beyond the scope of the original project – strategies include creating design examples, or training for others to implement the solution in new contexts. Adaptive implementation strategies combine sustained and expansive strategies to apply them to adapt and iterate the outcomes to new stakeholders and contexts – these include the development of transferable frameworks, design principles and guidelines.

Activity Theory

Activity Theory (AT) has been proposed as a framework for learning design with particular reference to mobile learning (Pachler et al., 2010; Sharples et al., 2005; Uden, 2007). In the wider context of technology-enhanced learning design, Activity Theory (Engeström, 2001) has been utilized to provide a framework for considering the different entities and facets and the interplay between them as an ecology for designing for learning with technology (Bozalek et al., 2014). Second generation Activity Theory delineates learning into several elements to understand and examine learner interactivity in socio-cultural settings that are made of entities and artifacts in a space at a given time (Engeström, 2001; Rozario et al., 2016) leading to action or change. As a result, learning in second generation Activity Theory is viewed as a collective interplay between tools (mediating artifacts), subjects (actors), object(ive) (goals), rules (constraints and guidelines), community and division of labour (who controls it)—together forming the activity system (Engeström, 2001). The object of an activity system leads to the overall goal of the interactions aligning with educational Design-Based Research goal of implementing transferable impact on learning. Contradictions in an Activity Theory system are tensions identified between the nodes within the activity system that hinder the outcome (Kwong & Churchill, 2023; Murphy & Rodriguez-Manzanares, 2008), whereas strengths of the bonds that exist between the nodes within the activity system enable the outcome (Kamanga & Alexander, 2021). Contradictions in Activity systems can be identified as primary (inner contradiction of one node), secondary (between nodes), tertiary (new versus old methods) and quarternary (between central and neighbouring activities). However a critique of Activity Theory is that it can be too complex for practitioners to have useful impact of practice (Pachler et al., 2010) so we have focused upon identifying contradictions without explicitly categorising them as the most practical for non-specialist discipline-based academics to engage with in a high-level analysis. Figure 2 represents a generic second generation Activity Theory system that was used in the development of the analysis template.

Figure 2

Generic Activity Theory analysis diagram (Original figure based upon Engeström, 2001 second generation Activity Theory)



Penuel et al., (2016) argue the case for utilising Activity Theory to inform Design-Based Research to help take examples beyond a simplistic intervention context to transformative experiments. AT emphasises the cultural (situated) context of a Design-Based Research implementation (Penuel et al., 2016). Sannino et al., (2016) argue Activity Theory can identify transformative participant agency beyond the theoretical designs initially identified by Design-Based Research. Greeno (2016) argues for the need to formulate causal design principles that apply directly to processes at the level of activity systems as an outcome of Design-Based Research. Thus the intersection between Design-Based Research and Activity Theory in educational research and design can be a model that drives educational technology praxis impact to move from 'within' to 'beyond' specific contexts as defined by Henriksen and Ejsing-Duun (2022).

Method

This paper explores the design of four examples of implementing Design-Based Research in different disciplinary contexts in higher education: Health Education (Galvin, 2023), Electrical and

Mechanical Engineering (Buskes et al., 2023), Biomedical Engineering (Lam, Cochrane, et al., 2021a), Music Performance (Osborne et al., 2022). The examples were chosen through purposive sampling from participation in TEL conference presentations and project leads were identified and invited to collaborate in a comparative retrospective analysis by the lead researcher. This paper builds upon and extends an initial brief descriptive multi-case study of the four examples (Cochrane et al., 2023) through a retrospective analysis drawing upon Bakker's (2018) five characteristics of design research combined with a high-level Activity Theory analysis of each example using a shared analysis template. This analysis is focused upon how these examples achieved transferable outcomes beyond their own specific contexts.

All authors of the example case studies are also authors of this conceptual paper and no project student participant data is used in the analysis of the implementation strategies and design principles derived from each project. Each example project obtained university ethics consent and followed ethical procedures for their participants including informed consent and anonymisation of participant data.

Retrospective Analysis Template

A common analysis template was used for each example (Cochrane, 2024) to enable comparisons across the different disciplinary contexts. This included addressing six elements: firstly, a project description identifying the pedagogical problem or innovation addressed. Secondly using Activity Theory to identify the constraints and strengths of the socio-cultural context. Thirdly describing the impact of the project on student learning outcomes. Fourthly identifying Bakker's 5 characteristics of Design-Based Research within the project. Fifthly defining the outcomes of the project as: Sustained, Expansive or Adaptive. Sixthly crafting a Design Principles Statement based upon the project implementation. The six-point retrospective analysis template was designed to help address the main research question and applied to the four examples:

> **Research Question:** What are the characteristics of Design-Based Research projects utilising technology-enhanced learning innovations in HE that support sustained, expansive or adaptive implementation?

Results

Case 1: Clinical Reasoning

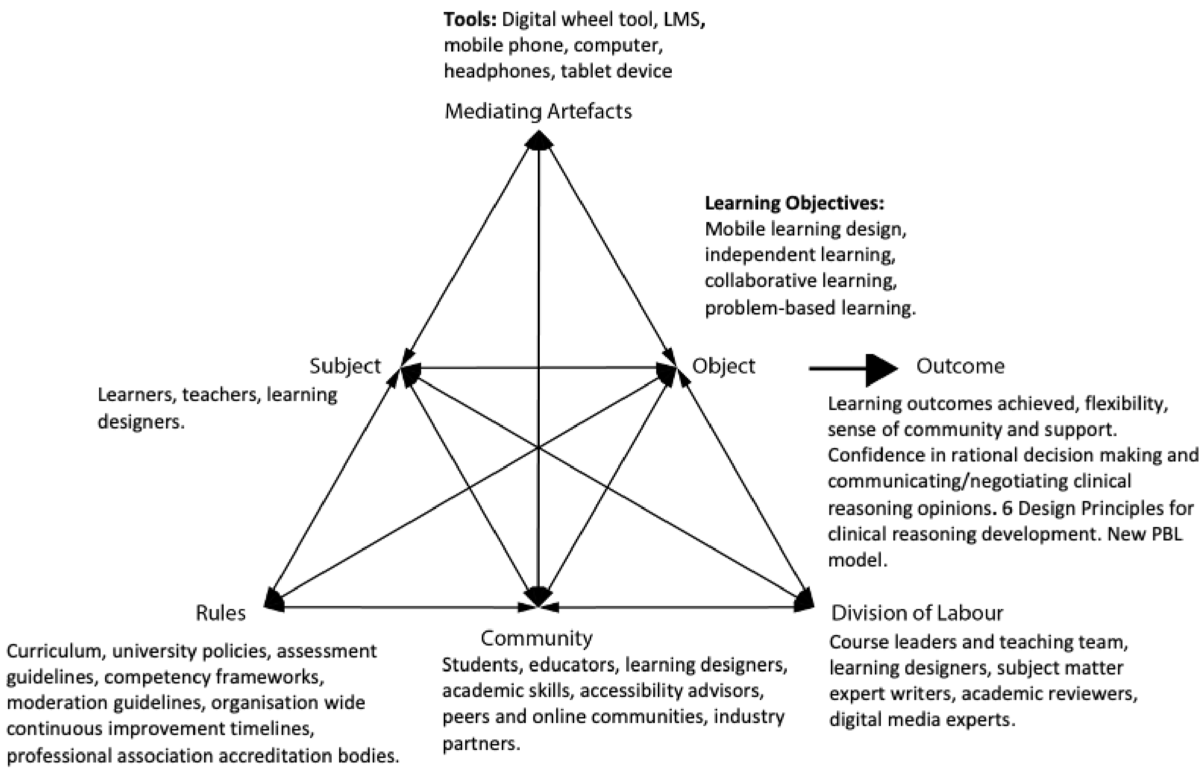
Clinical reasoning involves gathering and evaluating information to plan for clinical intervention. Using a uniquely developed hybrid group-based learning approach for this PhD project, moments of direct teaching alongside self-directed and peer learning was encouraged to instil confidence in clinical reasoning skills prior to learners entering workplace settings, student clinics and industry working environments. To understand 'what works' in practice, a longitudinal Design-Based Research framework was applied using the qualitative reflexive thematic analysis method (2019-2022). This study included twenty undergraduate health science and nursing course subjects at an Australian university across face-to-face, blended learning, and fully online learning platforms. Data generated consisted of 44 interviews, 20 focus groups, 10 participant and 65 researcher reflective journal entries. The research question addressed the following pedagogical problem:

How can combining independent online clinical reasoning analysis with group work support undergraduate health science students learning to perform rational decision making? (Galvin, 2023, p. 26).

Primarily, outputs of this study align to the original research goal for generating a solution to an experienced problem for enhancing clinical reasoning development. These were generated in the form of tangible (practical artefacts e.g. decision wheel tool and new problem-based learning or PBL design) and non-tangible (final themes, design principles, and scholarship learnings) original contributions (Galvin, 2023). Figure 2 presents an activity system of the project.

Figure 2

Clinical Reasoning Project Activity System



Using the lens of Activity Theory (AT) the interplay of artifacts, subjects, objectives, rules, and community, all involved in this study were key to inform what works in practice (Engeström, 2001). This did not come without moments of tension during the interplay. By virtue of engaging a Design-Based Research longitudinal research process in uncontrolled naturalistic learning environments, there were inevitable delays, unintended successes, and what could even be termed as 'failures' among real-world messiness of AT nodes working together (Bakker, 2018; Barab & Squire, 2004; Parmaxi & Zaphiris, 2020).

Contradictions developed due to issues of finance, resources, and the bounds of institutional policy/process that posed a certain level of restriction on design enhancement within the scope of this project. As an example, Design-Based Research action cycles were bound by strict institutional 'ticketing cycles' timing, rendering restrictions for deciding on and communicating improvement opportunities (Galvin, 2023). At times, tension existed between Activity Theory node ‘actors’ when exploring a solution for improvement during action- cycles. For instance, students and teachers often conveyed how the ‘simplicity’ of the decision wheel tool design was a strength, even when attempting a range of decision-making tasks that varied in complexity (Galvin, 2023). This perspective was not always aligned with designers/digital media expert thinking conceptualising the design of a decision-making tool to engage learners. Inspired by Fawns, (2022), instead of allowing the technology to fully drive teaching application of the decision wheel (technological determination) or encourage teachers to be the sole drivers of choosing what methods to use the decision wheel (pedagogical determinism), the act of mutually shaping ways to use the decision wheel (entangled pedagogy) was explored with input from various participants (Galvin, 2023).

The primary goal of the project was to explore how a problem-based learning (PBL) design could enhance decision making, through the lived experience of using an online decision wheel tool to practice independently and when collaborating in groups for clinical case studies (Author2, 2023). Categories of bounded rationality theory provided variables to guide and observe how the learning design approach and role of the teacher had influence on developing these clinical reasoning skills. This descriptive theory acknowledges that individuals’ rationality can be limited by three key elements which include 1) imperfect information, 2) cognitive limitations of minds, and 3) amount of time they have to make a decision (Nantha, 2017; Simon, 1991).

Problem-based learning as a central pedagogical approach became a lens to gauge how nursing and health science undergraduate students were developing clinical reasoning skills of ignoring part of available information to focus on fewer relevant predictors for a clinical outcome (Author2, 2023; Marewski & Gigerenzer, 2012). During action cycles, feedback was gained through focus groups, interviews, and journal entries, on student experience of using the decision wheel tool and engage in the hybrid problem-based learning design. Each cycle presented an opportunity to re-engage with literature to inform future improvements. Additional learning theories drawn upon included cognitive overload theory, transformative learning theory, and social constructivism to keep improving a problem-based learning design for learners (Galvin, 2023).

Outputs from this project make an original contribution to both practice and theory by offering a set of six final design principles (DP1-6) to assist enhancing clinical reasoning development for a situated context with implications for learning design, health science education, and higher education more broadly, positioning this project as adaptive in scope. Key recommendations include: (DP1) having a central teacher guide, (DP2) adequate coaching support, (DP3) simple learning designs, (DP4) time for reflexive practice, and (DP5-6) enhancing the ability for key participants to collaborate on curriculum. Additionally, an online decision wheel tool and a new problem-based learning informed model are key outputs to assist operationalising final design principles. Finally, this project generated new understanding into the potential expansion of bounded rationality theory to include the importance of collaboration for optimal decision making, along with how to adopt a cohesive and solely qualitative approach for Design-Based Research. Based on the outcomes of the project the following design principles statement can be proposed:

> To improve learning clinical reasoning skills, provide a central non-dominant teacher guide (DP1) and engaging coaching (DP2) to address information imperfection, harness a simple design (DP3) to reduce cognitive limitations, integrate time for reflexivity (DP4) to alleviate time constraints on learning, and finally, with the addition of vocalising and collaborating (DP5) and enhancing

stakeholder contribution (DP6) in learning design, it is possible to overcome the inability to collaborate for quality decision making.

Case 2: Interdisciplinary Engineering

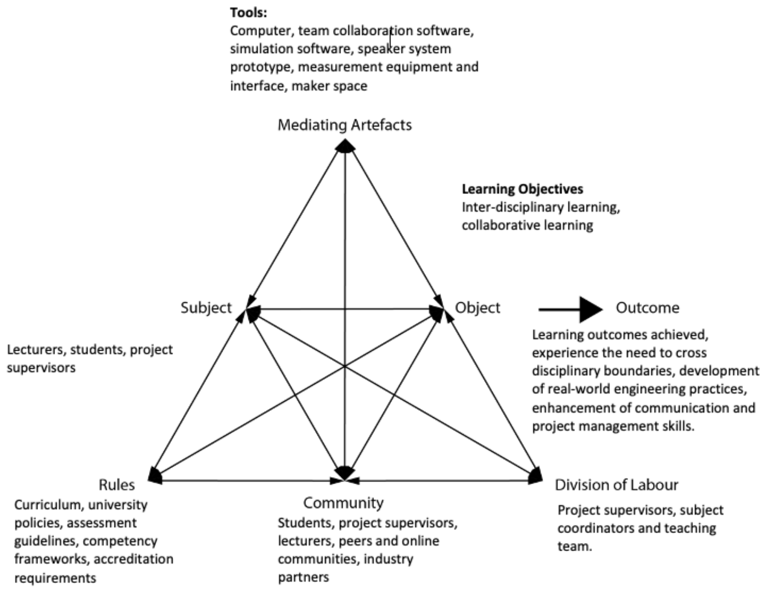
Engineers ultimately work in multi-disciplinary workplaces, where people from different disciplines work together and draw on their disciplinary knowledge, yet degree specialisations typically silo subjects that prevent students from interacting with those outside of their specialisation. As products and technology become increasingly complex, engineers can no longer do design in isolation. An important part of the design process is therefore to understand the interface with other disciplines of engineering and be able to specify appropriate requirements and verify that those requirements are being met. If groups of students in different engineering disciplines do not interact while at university, they are ill-prepared to do such design across disciplinary boundaries in the workplace. Moreover, if they are incapable of being able to formally specify *what* they require from other engineers, then they would not be able to verify that the design meets those specifications. This project seeks to address these issues through developing an inter-disciplinary team capstone design project, where students are required to integrate knowledge and methods from different disciplines in the design of a speaker system, an electro-mechanical-acoustic energy transfer system. The inter-disciplinarity of the project is framed around a loudspeaker design project that maps the complex transformations of energy that occur across natural disciplinary boundaries, leading to a synthesis of approaches from the different teams and a corresponding transformation of pedagogy (Cochrane et al., 2025). The project's research question addressed the following problem:

How can engineering students develop authentic interdisciplinary teamwork skills?

The speaker design project required a team of electrical and a team of mechanical engineering students (The subjects of the activity system) to go through an entire product design cycle process, whereby they needed to identify an appropriate application, specify the objectives and constraints, prepare a budget, model, design, simulate, build and test a prototype system and perform iterative refinements to their design. An activity theory mapping for the speaker-design project is shown in Figure 3, showing the key role that the mediating artefacts played in the facilitation of the project, which is a common aspect of project-based learning. Student teams would regularly meet F2F with the project supervisors to discuss progress and ensure that the aims of the project were achievable in the given two-semester timeframe. Both intra- and inter-team communication was required to be performed in dedicated team-focused software platform (Microsoft Teams) to reflect engineering workplace practices and for the project supervisors to be able to observe the interactions among the teams to assess how inter-disciplinarity was being practiced asynchronously beyond the F2F project meetings.

Figure 3

Activity theory analysis for speaker system design project



Students were surveyed at regular intervals during the project to observe their evolving views on the role their discipline played in the project and how they crossed disciplinary boundaries through interaction and communication with the other team. One of the difficulties encountered was ensuring that students used the dedicated team-focused software platform (Microsoft Teams) for their communication to capture their interactions. This is a key artefact that links the subject, community and object nodes in the activity theory mapping and a means to enhance students' communication and project management skills. Students' easy access to multiple messaging and communication external platforms created a contradiction with using a professional project management system to handle project-related discussions. A potential for further strengthening the connections to the community node would be to have a more active involvement of an industry partner as part of the community informing the project, who can provide feedback to help scope and design the project, ensuring that students are exposed to real-world engineering practices. This partnership not only enriches the curriculum with practical insights but also provides students with direct feedback from industry professionals, helping them gauge their skills and readiness for the workforce.

The speaker design project enhanced student graduate outcomes and employability by offering an industry-driven, interdisciplinary learning experience. The project used technology to promote cross-disciplinary interactions, fostering collaboration beyond traditional departmental lines. The project draws upon social constructivism (students work in teams with more experience supervisors), constructionism (building an actual loudspeaker system prototype), authentic learning (the teams are interdisciplinary and the project is real-world) enabling collaborative inquiry teams and heutagogy (Blaschke, 2021; Hase & Kenyon, 2007) or self-determined learning (student teams negotiate the project design goals within guided design considerations and self-organise team collaboration beyond the weekly supervised meetings). The project also improved students' communication and project management skills through team-management software platforms that also served as a reflective space. The project aimed to reshape engineering education by exposing students to inter-disciplinarity through considering the transformations of energy that occur at the discipline boundaries, mapping to a transformative learning design framework (Mezirow, 2018).

The student design teams initially scoped and defined the design goals for a loudspeakers system (in 2023 this was a two-way compact public address loudspeaker system, in 2024 this was a two-way studio monitor loudspeaker system). The second phase was the prototyping of a design specification via simulation and Computer Aided Design, followed by an actual loudspeaker system build. This was tested to evaluate how the system met the original design goals, with a final showcasing of the project and final system design report and build at the annual engineering project exhibition.

Serving as a model for effective inter-disciplinary teamwork, the speaker design project demonstrates the benefits of an integrated, industry-relevant approach to engineering education. It is envisaged that the project can act as a model for integrating core subjects from different departments within the Faculty of Engineering and Information Technology (FEIT), positioning this project as expansive. Based on the outcomes of the project the following design principles statement can be proposed:

> To develop authentic interdisciplinary teamwork skills for engineering students, design real-world team-based projects that require collaboration from multiple engineering disciplines that enable student team negotiation of project design goals and directly model transformative learning experiences.

Case 3: Transdisciplinary Engineering

Biomedical engineering is an engineering discipline that integrates mechanical, electrical, and chemical engineering concepts as well as programming/computation to tackle issues related to human health. The bionic limb project was an initiative launched to embed this transdisciplinarity in the undergraduate biomedical engineering systems curriculum at the university. It achieved this by redesigning four core subjects around the student-led collaborative design of a bionic limb prototype. These subjects included: Applied Computation in Bioengineering (BMEN20003), focusing on programming/computation; Mechanics for Bioengineering (BMEN30010), focusing on mechanical engineering concepts; Circuits and Systems (BMEN30006), focusing on electrical engineering concepts; and Biosystems Design (BMEN30008), focusing on unifying engineering design principles. The project aligns each subject with the design and analysis of a bionic limb specifically focusing on a sub-system (e.g. electronics, or mechanical design) relevant to the subject's intended learning outcomes and how it contributes to the degree overall. In BMEN20003, students develop a computer-based simulation of the bionic limb in motion, allowing for the prediction of forces at play in the system. In BMEN30010, students engage in the computer-aided mechanical design of the bionic limb to ensure that it can withstand the forces induced by its motion. In BMEN30006, students focus on actuating the motion of the bionic limb using a combination of electrical circuits and programming. Finally, in BMEN30008, students integrate the lessons learned in the preceding subjects to devise a similar biomedical device of their choice. The project research question addressed the following problem:

> How can engineering students develop transdisciplinary thinking in order to solve complex biomedical design problems?

The key pedagogical problem (Activity Theory outcome) addressed by the bionic limb project was the growing over-compartmentalisation of knowledge observed in biomedical engineering undergraduates. Here, it was observed that students tended to limit their applications of core concepts to subjects within which they were encountered and found it challenging to apply these across subjects in a transdisciplinary manner. Figure 4 presents an activity system of the project.

Figure 4

Activity theory analysis for the bionic limb project.

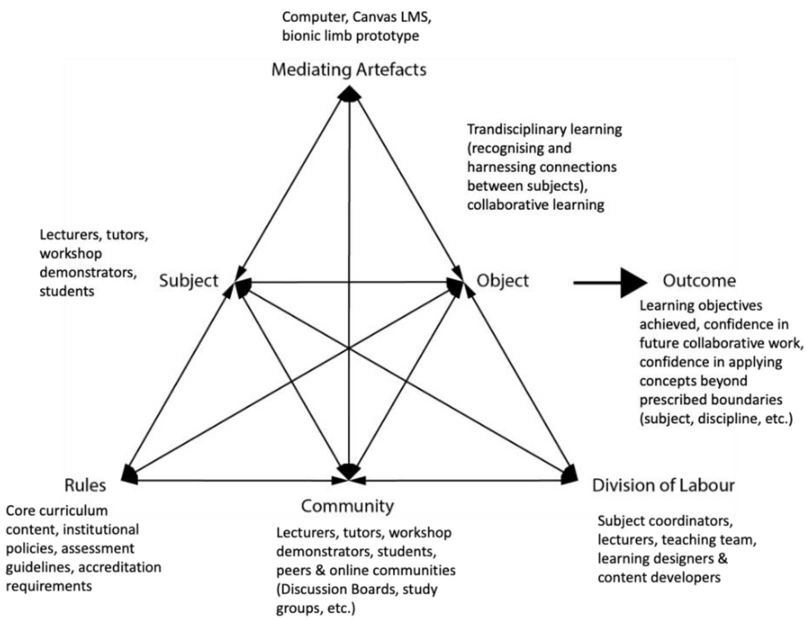


Figure 4 highlights that the course structure was determined by institutional rules – the traditional approach to compartmentalising of individual subjects that contradicted the integration of key concepts. This hindered for example, using programming/computational tools previously encountered to tackle problems in downstream subjects focusing on mechanical/electrical engineering concepts. Through this project, students gain an appreciation for transdisciplinarity by recognising how core concepts covered in each subject map to key sub-systems of the bionic limb (Mediating artefact). They are able to better recognise links and connections between subjects, equipping them to push disciplinary boundaries as fledgling biomedical engineers. The coordinators of the subjects involved in the bionic limb project were also indirect participants, having to deeply reflect on how their subject areas fit within the wider curriculum and how they might meaningfully connect with other subject areas.

The bionic limb project draws mainly on Papert's (1980) constructionist learning theory, where knowledge development in students is facilitated by the hands-on manipulation and construction of physical, shareable artefacts (giving rise to the active learning approach of project-based learning). It also draws on elements of social constructivism, as students are encouraged to engage in peer-to-peer and peer-to-instructor interactions to optimise their designs and solidify their mastery of core concepts. The bionic limb was chosen as a suitable artefact for the curriculum redesign as it featured key-subsystems that aligned well to existing core subjects within the undergraduate biomedical engineering systems major. In addition, its complexity allowed for it to be easily embedded into subjects to provide students with an authentic learning experience around collaborative engineering design, mirroring how real-world engineering work is done. Subsequent development of the project involved regular meetings with the stakeholders (subject coordinators, learning and content designers, etc...) to ensure that the revised content remained constructively aligned with intended subject and course-level intended learning outcomes, and that the content was pitched at the appropriate level. Multiple iterative improvements were made during this stage to ensure that all content and related hands-on activities were properly trialled – with scaffolding added where necessary – prior to the initial launch of the redesigned curriculum. Following the launch, the project team made use of regular institutional student feedback cycles (i.e. feedback from Student-Staff Liaison Committee meetings and End of Subject Surveys) to inform continual improvements to the project.

This also provides a sense of authenticity to the work being done as it directly mirrors real-world engineering projects. The project identified the following design principles: interventions should be developed with regular consultation from all relevant stakeholders, and all feedback and observations should be considered to allow for multiple rounds of iterative improvements prior to the initial launch. These rounds of improvements should continue even after the intervention is launched, informed by regular cycles of feedback and reflection. These principles align with constructionist and social constructivist learning theories and are in line with the cycles of continual improvement that feature in the Design-Based Research methodology.

The project demonstrated a sustained positive impact on participating students having gone through the revised curriculum. The project led to a decrease in the degree of over-compartmentalisation of concepts, which was the main impetus for the bionic limb project. Similarly, the project led to programmatic curriculum design, reflecting on the wider cross-curricular implications of changes made in these subjects, and led to incorporating transdisciplinarity in other subjects not involved in this specific project. The teaching team were recognised with a faculty teaching innovation award (Rajagopal et al., 2023). Through multiple shared outputs (Lam, Cochrane, et al., 2021a, 2021b; Lam, Cochrane, Rajagopal, et al., 2021) the project has also inspired the launch of similar projects focusing on embedding transdisciplinary thinking in students in other departments and used as an example in a curriculum design guide (Cochrane, 2022). This includes the previous example2 that focuses on developing a Capstone project model with cross-disciplinary teams of mechanical and electrical engineering students working on loudspeaker design. In terms of outcomes and impact, the implementation strategies of the bionic limb project can be positioned as adaptive. Based on the outcomes of the project the following design principles statement can be proposed:

> To promote transdisciplinary thinking in the context of engineering, curricula should be anchored to artefacts that are sufficiently complex to allow students to engage in meaningful hands-on collaborative design and experimentation, and to explore problems that can only be encountered at the boundary of traditional engineering disciplines.

Case 4: Performance Self-efficacy

The final project example is based in the context of music performance education. Performance anxiety is a pervasive and frequently debilitating difficulty faced by many performers associated with negative impacts on performance quality, psychological distress and deterioration in confidence. Simulated environments offer performers a chance to practice strategies for managing anxiety, enabling them to prepare for optimal performance in high-stress situations. The Virtual Performance Lab project explored the use of a simulated concert performance environment in virtual reality (VR) to deliver a performance psychology intervention for tertiary music students across two music performance subjects. The intervention taught performers to down-regulate anxiety and improve focus and resilience in two ways: Firstly students learned and implemented the 'centering' technique comprising of goal setting, breathing, guided muscle relaxation and visualisation immediately before beginning to play or sing a musical excerpt of their choosing; and secondly practicing this technique prior to performing a musical excerpt in a virtual performance hall. The project research question addressed the following problem:

> How can performing arts students develop performance anxiety management techniques in safe yet authentic learning scenarios?

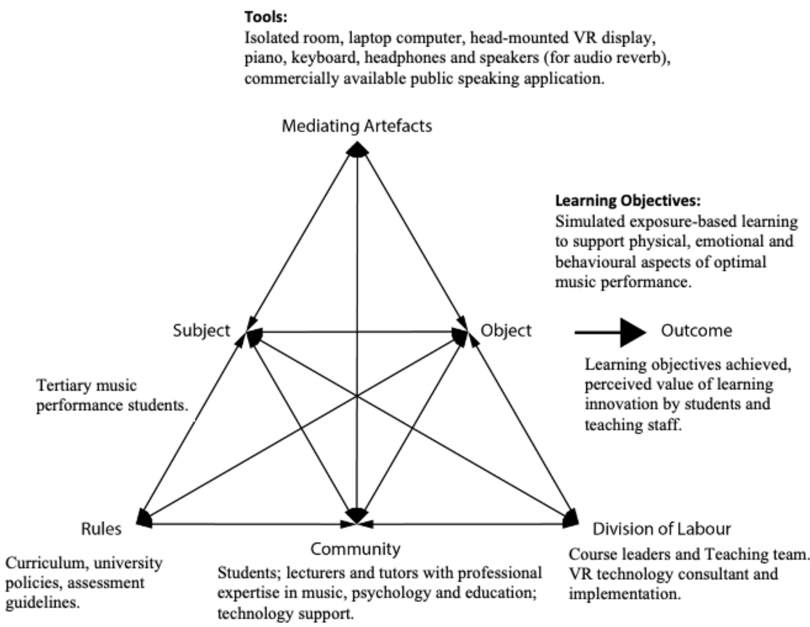
The theoretical approach draws from the epistemology of Performance Psychology - a branch of psychology that focuses on factors that facilitate optimal performance. It adopts a heutagogical approach to foster students' self-determined learning, exemplified by the practice of a performance-directed mental skills technique ('centering'), that was taught to students during the project (The activity system learning objectives). This technique has a proven efficacy for reducing debilitating performance anxiety whilst simultaneously improving performance preparation, confidence, courage, focus, concentration, and performance resilience in conservatorium music students (Osborne et al., 2014). The design for the project incorporated learning from prior studies and student feedback (Osborne et al., 2022; Osborne, 2020; Osborne et al., 2014). Prior to the first iteration, students were asked about their experience of using VR (Mediating artefact), and their motivation and apprehension about the use of VR in a music performance context. Students were then prompted to reflect on their experience of playing wearing a VR headset before, during and after each VR exposure. Figure 5 presents an activity system of the project.

A core strength of the project was the community – a close working relationship between academic and professional staff in delivering the intervention. This collaboration allowed access to a range of mediating artefacts and a clearly delineated division of labour, which enabled the successful execution of the intervention. However, the project's success was contingent on the physical presence of a performance psychologist during each individual intervention and the extensive technological support of a VR expert. This reliance on the division of labour and equipment-intensive requirements as mediating artefacts presented a significant challenge to the ongoing adoption of the protocol. The need for technological support, including a dedicated, well-equipped room, and the financial implications of purchasing equipment, highlighted the intervention's cost and logistical barriers. Additionally, the reliance on a commercially available application hindered the project's ecological validity.

The project progressed through cycles of design and redesign: Analysis, Design, Implementation, Evaluation and Redesign. The analysis identified the problem of reducing performance anxiety for music students through an authentic immersive learning experience through a literature review and establishment of a collaborative design team of developers, students and academics. The design stage involved the design of an authentic immersive performance simulation environment and evaluation methods. This was followed by iterative implementation, evaluation and re-design through student-feedback informing design refinements in VR headset model (from fully enclosed to one that had a gap below the visor so pianists could see the keyboard when playing) and replacing audio output using headphones with room speakers and reverb.

Figure 5

Activity theory analysis of the Virtual Performance Lab intervention



The future pedagogical applications of this project extend beyond the disciplinary boundaries of music. Simulation training is used to develop performance skills in various disciplines, particularly where in-situ training is either impossible or unsafe to implement. Such training enables learners to acclimatise to real-life stressors and anxiety-inducing scenarios in physically and/or psychologically safe environments. Through the development of design principles and training materials adaptable to broader contexts, the project has the potential to inform future teaching and learning interventions in other disciplines that encounter high-stress and/or dangerous scenarios, such as medical interventions, sports, public speaking, and other performing arts practices, positioning the project as adaptive. The adaptive implementation of the project has combined sustained impact depth with expansive application breadth, resulting in transferable frameworks, design principles, and guidelines applicable across diverse fields. Based on the outcomes of the project the following design principles statement can be proposed:

> To help students manage debilitating performance anxiety in tertiary education contexts, provide a VR music performance simulation incorporating stress-inducing performance scenarios, in which students can practice a goal-directed mindfulness and visualisation process, thereby offering an authentic, naturalistic and psychologically safe opportunity to practice strategies that will enable them to optimise their performance in high-stress situations.

Discussion

The analysis of the four Design-Based Research project examples addresses the research question “What are the characteristics of technology-enhanced learning innovations in HE that support sustained, expansive or adaptive implementation?" through highlighting common characteristics and provides examples of design principle statements in a variety of discipline contexts. A high-level Activity Theory analysis of each project helps to situate these designs in their socio-cultural contexts and identify contradictions and strengths of each activity system and highlight the transferable outcomes explicitly. The projects are also mapped using the Henriksen and Ejsing-Duun (2022) implementation typology to identify implementation strategies for wider adoption (Table 1).

Activity Theory System Contradictions and Strengths

As observed in each of the four examples, a Design-Based Research approach requires embracing the unexpected and 'messy' elements of learning and teaching to understand 'what works best in practice' (Bakker, 2018). One way to navigate this is to use Activity Theory analysis with Bakker's five characteristics for an individual project and across a group of projects as this article has done. This will help identify contradictions and strengths, consider theory development and how a design intervention develops, ensuring that prospective, reflective, interactive, and real-world components remain consistent and maintained.

The Activity Theory analysis of each example allows identification of context specific socio-cultural contradictions that may have impacted the evidence or helped support any of Bakker's five characteristics of Design-Based Research projects. For instance, the Activity Theory analysis highlights issues concerning financial, resource, and institutional boundaries, each influencing how much change was possible. Additionally, each Design-Based Research project had a reliance on 'actors' to work together to improve a design artefact. The reliance upon student design teams can hinder the intervention design when the lack of real-world teamwork experience can lead to pushing out project timeframes with missed milestones or miscommunication between the teams. Activity Theory analysis also highlights tensions that can arise within project development teams comprised of different perspectives and key performance indicators. Identifying these tensions early and building team skills in how to resolve contradictions pragmatically is one key to sustaining Design-Based Research projects. The following sections explore the implications for practice from the four examples in relation to Bakker's five characteristics of Design-Based Research.

Bakker's Five Characteristics of Design-Based Research

Theory development

The development of practical theories about learning (or praxis) is closely aligned to the intervention design of each project. The clinical reasoning development project recommended that bounded rationality theory could include an additional key element to highlight the importance of collaboration in optimal decision making. The loudspeaker design project has an interdisciplinary focus exploring the application and extension of theories of learning that enable authentic interdisciplinary teamwork within the context of Engineering education. A scoping review for the loudspeaker design project highlighted that this is an under theorised domain for this context with limited examples of theoretically grounded practice. The loudspeaker design project outcomes therefore make a significant contribution to this field (interdisciplinary engineering education). The Bionic Limb project applied transdisciplinary collaboration explicitly into an implicitly transdisciplinary biomedical engineering degree and has served as an example of explicit transdisciplinary curriculum design within a Design-Based Research curriculum design guide. The Virtual Performance Lab project integrates learning theory from multiple discipline contexts creating a new transdisciplinary learning design framework. This paper contributes to theory development through articulating an analysis and potential design model that combines Design-Based Research with Activity Theory to amplify the transferability of project outcomes through identifying context specific socio-cultural contradictions and strengths.

Intervention design

Design-Based Research projects focus on designing a solution to an identified pedagogical problem and this is achieved through the design of artifacts and design principles that facilitate pedagogical innovation. The projects illustrate that incorporating research teams that include a collaboration between educational researchers, discipline experts and student design teams lead to improved learning outcomes. However, the loudspeaker design project and the bionic limb project both highlight how the reliance upon student design teams can hinder the intervention design when the lack of real-world teamwork experience can lead to pushing out project timeframes with missed milestones or miscommunication between the teams. As highlighted in Table 1, transdisciplinarity is a common feature of the three adaptive projects, while interdisciplinarity resulted in an expansive project. Building transdisciplinarity into a Design-Based Research project clearly enhances the transferability of the resultant design principles into wider contexts, however student teams have limited experience of learning from and communicating across discipline boundaries. All the projects are longitudinal, being multi-semester projects that are typically over a full academic year or at least two semesters, thus building longitudinal scope into Design-Based Research projects is critical to impact on learning outcomes. Finally, adopting the role of an ‘engineer of nodes’ (Where ‘nodes’ are the Activity system relationships between the key stakeholders) is key for a Design-Based Research researcher to support success of a project by guiding reflection and compromise during the iterative cycles of design intervention (Bakker, 2018; Galvin, 2023).

Prospective and reflective components

The longitudinal nature of the projects facilitates both prospective and reflective components. These can be reified in outputs such as showcases of practice, webinars, development of practice guides, recognition through institutional awards and collaborative SOTL case studies that enable dissemination of project designs and focus reflection on the impact of these. When undertaking a Design-Based Research project the central researcher/research team must engage in regular touchpoints of reflection to assist in making connections between actions and outcomes during iterative cycles in a reflexive capacity (Armstrong et al., 2020; Bakker, 2018; Collins, 1992; Hoadley & Campos, 2022). This was noted across the examples and can be expressed as taking on an inbetweener or broker role (Ajjawi, 2022), that moves freely back and forth between key communities and stakeholders to assist interdisciplinary exploration and review.

Iterative

As well as being longitudinal the examples highlight that Design-Based Research projects should also integrate iterative cycles of feedback, evaluation and redesign leading to refinement of how pedagogical practice map to the intended learning outcomes. The typical academic calendar of semester long subjects with breaks between semesters provides opportunities to evaluate the impact of the projects at the end of a semester and redesign elements of the projects for the following semester. A key measurement of validity of a Design-Based Research project is the ability to produce meaningful change with stakeholders to increase alignment of theory, design, and practice in situated contexts (Design-Based Research Collective, 2003). Planning times when all actors can contribute to providing feedback and improving a design artefact is a key role of the Design-Based Research central researcher/research team for the iterative momentum to continue successfully and for tensions to be reduced.

Enabling real work

The four examples illustrate how Design-Based Research projects can focus upon authentic real-world problems and applications. Expansive and adaptive Design-Based Research projects embed their design principles in outputs for transferring practice in the form of showcases of practice, webinars, development of practice guides, and collaborative SOTL case studies, through which the projects broker their practice to wider audiences beyond their own communities of practice. Showing evidence of these scholarship influences becomes part of the intangible outputs of a Design-Based Research project (Bakker, 2018; Design-Based Research Collective, 2003; Domínguez, 2017; Herrington et al., 2007; Parker & Herrington, 2018). Explicitly crafting design principles statement from Design-Based Research projects provides examples of pragmatic application of the design principles to achieve the project learning outcomes that can be applied to other relevant contexts, resulting in expansive or adaptive impact.

Implications for Transferable Practice

As a methodological framework, Design-Based Research has a dual focus, to be *instrumental,* by manipulating the environment, and to *observe* the naturalistic ways students engage with learning (Bakker, 2018; Galvin, 2023). Design-Based Research interventions aim to produce transformative learning experiences. Articulating a clearly defined design principles statement for each example that is informed by both an Activity Theory analysis and built upon Bakker's five characteristics of Design-Based Research enables positioning these projects as transformative learning experiences that move beyond sustained implementation to expansive and adaptive implementation that can be applied to wider contexts. Unpacking Design-Based Research through a clearly identified implementation and evaluation framework as introduced in this paper is one way to scaffold Design-Based Research project designs that explicitly aim to develop transferable design principles that produce outcomes that move beyond sustained implementation to wider impact through adopting expansive and adaptive strategies as illustrated by the four examples in Table 1.

Table 1

Mapping the Design-Based Research project examples to sustained, expansive and adaptive implementation strategies

Time and budget	**Stakeholders and context**	Example Design-Based Research project outcomes
No explicit implementation beyond the project		
Within	Within	All the example projects aim to have wider impact beyond the project.

Sustained Implementation		
Beyond	Within	All the projects aim to reach stakeholders and contexts beyond the initial project implementation.
Expansive Implementation		
Within	Beyond	Case example 2: Interdisciplinary engineering Developed a model for interdisciplinary collaboration in Engineering education. Outputs from the project include a scoping review and case study reports.
Adaptive Implementation		
Beyond	Beyond	Case example 1: Clinical reasoning Models a transdisciplinary project team and identified 6 design principles with implications for wider contexts. Practical outcomes included the development of an online decision wheel tool and a Problem-Based Learning model. The project contributed to the expansion of bounded rationality theory and implementation at a new institution beyond the original institution. Case example 3: Transdisciplinary engineering The project developed a model for integrative transdisciplinary assessment design that has been adopted in other Engineering contexts and been featured as an example in a Design-Based Research design guide. The project has been recognised with a faculty teaching innovation award. Case example 4: Performance self-efficacy The project demonstrated transdisciplinary collaboration between performing arts and psychology using immersive reality. The project was awarded faculty budget to extend project to generate guidelines for wider faculty implementation and aims to impact wider contexts beyond the initial faculty across the university.

Sustained implementation strategies include applying for institutional funding for each project, framing each project explicitly within a Design-Based Research framework from inception enabling identifying design principles that leverage the project strengths while addressing contextual contradictions. Expansive implementation strategies include creating design examples through outputs from each phase of the projects (as illustrated in Figure 1) such as presenting case studies at institutional showcase events (Webinars and Symposia), recognition of impact through institutional teaching and learning innovation awards and presentations at international conferences allowing others to implement the solution in new contexts. Adaptive implementation strategies include the development of reusable artifacts such as transferable design frameworks published in peer-reviewed outputs and open-access design guides.

Limitations

A limitation of any conclusions is the purposeful sampling of the included examples that were chosen for their potential to demonstrate transformative learning. This analysis has focused upon the development of design principles from each project and how these have been disseminated. A limitation of a retrospective analysis is that the Activity Theory mapping is made post intervention in these examples. Applying this method as a future design framework for new contexts that combines both Activity Theory and Design-based Research, the Activity Theory analysis should be used both before the interventions and after the interventions to identify the contradictions within the system and how the intervention was then designed to address these contradictions and transform the activity systems. Additionally integrating third generation Activity Theory's focus upon multiple, networked activity systems can be used to identify broader interconnected drivers of change and learning (Engeström & Sannino, 2021) within Design-Based Research projects. However, maintaining a high-level analysis approach that does not create theoretical roadblocks for wider practice is important for implementation. The authors hope to generate interest in collaborating with other TEL Design-Based Research practitioners to create an international community of practice to further develop and share transformative learning designs integrating Design-Based Research and Activity Theory analysis.

Conclusion

Answering the research question "What are the characteristics of technology-enhanced learning innovations in HE that support sustained, expansive or adaptive implementation?" each of the four examples of Design-Based Research TEL implementation in different higher education discipline contexts illustrate the five characteristics of Design-Based Research outlined by Bakker (2018).

> Informed by an Activity Theory analysis the four projects illustrate common features of transformative learning that is either expansive or adaptive though outputs that share praxis and the development of design principles.

The four examples illustrate common contradictions and strengths to consider regarding 'actors' working together on a common goal of design improvement and solving a learning problem through implementing TEL.

> Importantly, planning and skills are needed to navigate the impact of rules, community and the division of labour activity theory nodes for a Design-Based Research researcher/team.

The authors hope that the analysis template may also function as a design framework for others exploring the potential of Design-Based Research to transform learning in other TEL contexts. The analysis template is open-access available for download and creative commons reuse (Cochrane, 2024).

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