A Tangible Approach to Teaching and Learning Search-Space Concepts in Higher Education

Clifford De Raffaele, *Member, IEEE*, Mark Borg, Serengul Smith and Orhan Gemikonakli

***Background*—The teaching and learning of artificial intelligence (AI) concepts has proliferated in higher education institutions (HEI) as AI research is ubiquitously integrated amongst different courses. Whilst computer-based approaches have often helped in delivering these educational topics, the foundational notions of search-spaces still pose a challenging threshold concept.**

***Contribution*—This paper proposes the design and adoption of a Tangible User Interface (TUI) architecture to aid students in conceptualizing these complex notions.**

***Application Design*—The contribution defines the unique design requirements for mitigating the challenges of integrating such an educational approach in HEI whilst retaining the pedagogical benefits sought after from tangible interactions. The proposal further describes the implementation and development considerations to provide an effective active learning approach using TUI through the interweaved design of physical and digital interactive components.**

***Intended Outcomes*—An evaluation methodology is explained in this paper which investigates the effective ability of the proposed tangible approach to aid conceptual understanding of search-space exploration. This intended outcome is evaluated experimentally via the deployment of the proposed tangible approach within a university AI program and experimental data is collected to objectively assess students' improvements in knowledge gain and problem-solving abilities.**

***Findings*—The proposed tangible methodology is experimentally evaluated against current software-based educational techniques for teaching and learning AI search-spaces. Statistical analysis of the experimental findings outlines the effectiveness derived from the developed interactive TUI methodology to aptly aid HEI students in furthering their understanding of complex and abstract concepts using constructivist and collaborative active-learning pedagogies.**

***Index Terms*—Artificial Intelligence, Computer-Aided Instruction, Educational Technology, State Search Spaces, Tangible User Interface**

I. Introduction

The proliferation of AI has progressively evolved the domain from a specialization in computer science to nowadays present in most aspects of software and systems engineering. This advancement has naturally led HEIs to introduce and teach the foundational concepts of AI within an ever-growing portfolio of courses in various disciplines [1].

Nevertheless, the teaching and learning of fundamental AI concepts such as: search, knowledge representation, and machine learning prove a challenge to deliver and understand within undergraduate courses for both lecturers and students [2] alike. This claim has been supported by various educational research, outlining difficulties in both explaining the abstract conceptual content involved and those experienced by students in visualizing these notions [3]. These inherent difficulties further hinder students in applying and understanding AI theory from both conceptual viewpoints as well as from the required practical and technical perspectives [2].

Furthering the complexity of introducing AI within education is the breadth of topics that are entailed within the field, which often leads to overwhelming students with an incoherent set of disjoint topics. This phenomenon is commonly referred to as the 'Smörgåsbord' problem. To aid correlate these domains together, the foundational concept of state-space-search (a.k.a. 'search-spaces') has commonly been utilized as a unifying theme for AI topics [4], providing a constructive platform onto which students can amalgamate AI understanding [3]. The vital concepts of search-spaces are nontrivial to explain and understand and often lead themselves to a threshold concept within introductory AI courses [5].

Unfortunately, the technical and psychological dimensions which students need to mentally map these abstract concepts presents a challenge for comprehension [2]. Students thus struggle to visualize the high-dimension reasoning required whilst at the same time be able to technically implement these abstract algorithms [6]. The limited capabilities of traditional teaching pedagogies involving tutor-based instruction [5] and traditional visual media [7] further constrain students' ability to comprehend searching algorithms, consequently reducing the effectiveness of AI lectures [8]. This inadequacy led to the development of educational tools which aim to help students in learning and understanding these abstract themes [9].

Using graphical user interface (GUI)-based software, educational technologies were consequently developed to explain search algorithms via visualization tools [8]. Additionally, the engagement of edutainment alternatives which adopt games to teach AI concepts has increasingly

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gained popularity with HEIs [10]. The use of gamified educational software for search-spaces is further favored for its ability to exemplify conceptual understanding using classic puzzles such as; tic tac toe, river-crossing, missionaries and cannibals and the eight-queen problem [11]. Moreover, the gamified approach to such transport puzzles exposes students to real-life logistical contexts, which aid to exemplify conceptual processes such as 'path-planning' and 'search methods' whilst increasing students' engagement and learning motivation [12].

Regrettably, the focus of games on their inbuilt animated graphics and the enjoyable user experience during puzzle solving often limits the educational elements presented to users to visualize and understand the underlying concepts [2], [13]. Thus, this leads to the conceptualization of AI search-spaces to be still widely regarded as a difficult threshold to teach and learn [6], [14]. Moreover, the limited and generic interaction capabilities of GUI frameworks using conventional personal computer setups fail to provide users with an immersive educational experience [15]. This hinders the students' ability to undertake creative and collaborative learning interactions, thus impeding the effectiveness of learning pedagogies adopted in HEI lectures [16].

To this end, this paper presents an alternative approach to introduce undergraduate students to AI search-space concepts using an engaging and interactive tangible approach. The proposed approach is evaluated through an experimental setup and the findings are discussed. Following a review of tangible technology in section II, the paper describes the development of an interactive tangible architecture approach in section III, which is further detailed with design considerations aimed to mitigate the educational challenges faced in HEIs. Section IV outlines an experimental deployment of the proposed approach within an AI university course, which is evaluated in detail for its effectiveness to aid conceptual understanding and exploration of search-spaces in section V. Finally, section VI draws a conclusion to the presented study discussing the suitability of tangible educational frameworks for teaching and learning abstracted and complex concepts.

II. Tangible Technology

TUIs have garnered sustained interest for their innate ability to interweave the physical and digital domain [17]. This is achieved by manipulating digital information through triggered behaviors and tangible manipulations, providing users with a richer interaction environment and augmentation of the physical domain [18]. This multi-sensory educational technology thus heightens users understanding of the engaged domain, whilst interacting in an enjoyable environment [19]. These benefits, intrinsically promote TUI education for its student-centered approach to learning whereby the interacting users directly control the learning pace and content [20].

Together with the hands-on and experimental aspects of physical setups, TUI architectures are able to provide a platform for tangible thinking, which augments student cognitive skills [17]. Moreover, the multitude of sensory engagement channels utilized by TUI systems provides an immersive interactive experience which enhances students' problem-solving abilities [21]. Compared to student's educational performance with GUI software-based technology, TUI systems are slower in problem-solving, yet allow students to provide more intricate and complex solutions and achieve an overall higher solve rate [7]. Moreover, the unique shared-workspace scenario provided by TUI architectures intrinsically promotes the adoption of collaborative learning [22]. The fluid interactive environment naturally encourages collaborative interaction by actively guiding students to interact simultaneously with manipulate multiple tangibles. This helps provoking group discussion whilst inherently maintaining students' awareness of collegial actions on the interface [23].

Coupled with the ability to captivate students' attention and provide physically engaging activities, these teaching and learning capacities quickly led to tangible approaches being integrated within active pedagogies for young children [24]. Effective TUI implementations were thus able to deliver concepts beyond learners' age-associated abilities [17] and successfully introduced children to abstracted concepts in spatial reasoning, musical impressions and mathematics [25]. Within secondary education, tangible approaches have also been able to facilitate student introduction to abstracted notations. Amongst others, setups like *Augmented Chemistry* [26] allowed students to visualize molecular structures, and the commercialized *LEGO Mindstorms*^{TM} assemblies have provided a more engaging approach with which to introduce programming concepts to students [27].

Whilst the experience of integrating learning in an attractive, fun and interactive manner provide positive results for children, TUI architectures fail to scale with equal effectiveness when utilized with adult higher-education users [28]. Notwithstanding the need outlined by educators for developing tangible technology to teach highly complex subjects [29], developments of this technology in HEI have yielded mixed results for conceptual understanding [30]. Whilst TUI frameworks such as *URP* [31], enabled students to positively interact with augmented architectural models, the specific and limited capacities of TUI systems failed to effectively conceptualize advanced and complex mathematical [32] and anatomical concepts [33].

The inconsistencies in conveying the sought benefits during teaching and learning in HEI outline the distinct difficulty faced with abstract subjects and the consequent need for tangible educational technology to specifically address the domain's challenges [34]. Thus, following the appropriate design and development considerations to mitigate the identified TUI limitations, this paper presents a tangible architecture which carefully addresses the design challenges for HEI education.

III. Proposed Tangible Approach

The contribution of this paper lies at the confluence of the limitations identified in literature by describing the adaption of tangible technology to address the educational challenges of teaching and learning AI. Specifically, this paper articulates the TUI design considerations undertaken to effectively aid in the delivery and understanding of threshold concepts within search-spaces. In tandem with active learning literature and the educational benefits harbored within TUI, the proposed tangible approach describes the physical and digital interactive paradigms designed within this technology. This embodied interaction approach aims to simplify the conceptual understanding of search-spaces by integrating appropriate design considerations to overcome the complexity and abstraction challenges experienced in HEI contexts.

To contextualize the search-space problem concepts, whilst embedding the gamification benefits within the proposed tangible approach, a variety of educational puzzles were investigated as outlined in literature [11]. Whilst the familiarity of students with transport puzzles is an asset which is often exploited in educational games, popular versions of these puzzles; such as *Towers of Hanoi* and *Missionaries and Cannibals*, were not deemed appropriate due to their inherent well-known solutions [35]. Furthermore, the limited complexity of these puzzle instances fails to provide an engaging problem-solving difficulty to HEI mature students, thus hindering their appreciation of underlying concepts [36]. To this end, a less popular transport puzzle was selected from the 'river-crossing' genre, which is exemplified in the *Japanese family river-crossing* puzzle scenario [37]. This example provided a suitable level of problem difficulty due to its exponential search-space size growth as the problem increases in length and complexity, together with a set of non-trivial problem constraints [38]. This ensured that students would be exposed to an educational knowledge challenge further to an enjoyable game puzzle.

A. Physical Overview

The complex nature of search-space problems necessitated the TUI architecture to possess a large interactive surface which would be able to accommodate the visualization and scale of the AI algorithm. Furthermore, the ideal setup needed also to comfortably allow adult students to engage in collaborative interaction whilst learning. To this end, following a review of architectures in the literature [17], [39], a tabletop TUI architecture was selected for implementation. This was chosen for its interaction style, which rather than using connecting blocks in assembly style setups, allowed for a more suitable interaction by mature students within an HEI context. Furthermore, the tabletop architecture provided the ability to collectively exemplify concepts to student cohorts within an interactive laboratory setup.

Based loosely on the MCRpd interaction model [40] and integrating the reacTIVision computer-vision based framework [41], the proposed approach interfaces the physical and digital domain by passively tracking and actively engaging student interaction. This is achieved on a tabletop interactive surface, which as depicted in Fig. 1, is illuminated by a short-throw digital projector, and captured from a wide-angle camera sensor underneath. The lenses on these devices provided the capability of deploying a 1.3m^2 interactive tabletop surface, made from 3mm semi-transparent acrylic, at a net height of 90cm. This height constraint allowed the visualization, reach and interaction with the educational setup by multiple students concurrently, hence promoting collaborative interaction.

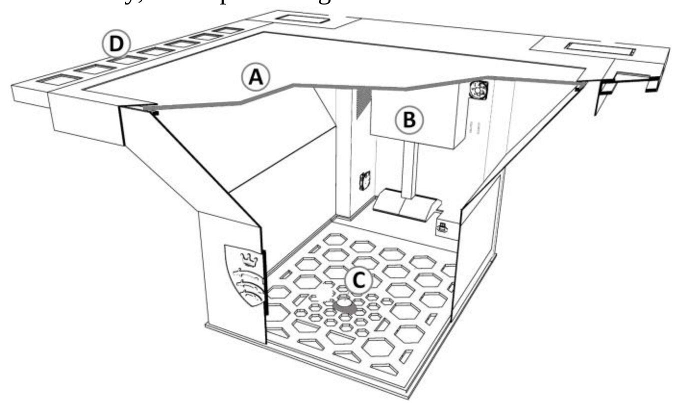

Fig. 1. Construction cross-section of the proposed tangible approach:
a) Tangible interactive surface,
b) Short-throw projector,
c) Wide-angle CCD camera with IR band-filter,
d) Side trays with illuminated TUI placeholders.

To further engage and interact with students, the proposed architecture adopts the use of an innovative TUI interaction paradigm, by integrating a set of active TUI placeholders adjacent to the tabletop surface as highlighted in Fig. 1d. These interactive elements were controlled by the proposed system using an Arduino^{TM} microprocessor and enabled the TUI architecture to direct and provide appropriate feedback on the use of the tangible elements in a non-coercive manner, thus further aiding the adopted educational approach.

B. Tangible Interaction

The interactive engagement of students with the proposed approach was achieved via the manipulation of dedicated 3D objects. These physical components, shown in Fig. 2, were composed of aptly selected figurine models, which through *apriori* student familiarity and association, enabled the intrinsic embodiment of native properties. The design of these objects also took into consideration the size and weight of manipulatives to ensure a comfortable and ergonomic interaction. Thus, each object was placed on a 5cm x 5cm acrylic plastic base, which was colored on top whilst affixed with a reacTIVision fiducial marker underneath [41]. The latter enabled the TUI architecture to passively track the physical location and rotation of each unique object which was provided as input to the system using the TUIO protocol [42].

Fig. 2. Tangible manipulatives adopted during the river-crossing context:
a-c) Figurines representing the exemplified puzzle characters,
d) Hint request tangible shaped as a life-jacket,
e) Search-space manipulative shaped as a magnifying glass,
f) Bidirectional river-crossing raft with passenger/driver configuration.

Various design considerations were undertaken to aid the conceptualization aspects of the developed scenario as well as promote engagement with the proposed TUI approach. These are systematically detailed below:

- Characters (Fig. 2a-c) – These figurines were designed to intrinsically relate to the specific characters in the puzzle scenario providing an intuitive association to the user. A carefully designed color-scheme was adopted on these objects which visually reinforced algorithmic puzzle constraints by ingraining an association between groups of linked characters. To reflect another constraint on the allowed travelling permutations of characters, potential raft *drivers* were equipped with an oar to facilitate the distinction and tangible selection by students.
- River-crossing raft (Fig. 2f) – This pivotal tangible was designed in line with the 'token-and-constraint' tangible principles [43], whereby a mechanical restraint was adopted to aid students in navigating through the potential search-space. As illustrated in Fig. 2f, the restriction was designed to enforce the algorithmic rule of ensuring at least one *driver* character is present in each valid transit combination. To this end, symmetrical mechanical designs were developed on respective figurines to aid students in intuitively identifying roles without distracting concentration from the search-space navigation and conceptualization. Moreover, to prompt the user towards rotational interaction with the tangible, the raft was designed in a circular shape with pointed edges which served as physical dial-pointers to select digital information.
- Tangible Controllers (Fig. 2d-e) – These input manipulatives enabled students to interact in a more engaging manner with the proposed TUI setup. The use of iconic models such as a life-jacket tangible was designed to allow students to seek assistance on valid search-space combinations if students remain stuck in a state for longer than 12 seconds. The magnifying glass object, on the other hand, allowed students to tangibly navigate through the explored search-space and revert to previous states by appropriately undertaking physical positional manipulation and selection.

C. Graphical Interaction

The interlacing and embodiment of digital augmentation on these physical models is primarily obtained via the perceptual and computational coupling of visual information projected onto the tabletop interactive surface. Thus, a graphical user interface was specifically developed for this TUI approach which by vertically splitting the interactive surface as pictured in Fig. 3a displayed the river-crossing scenario together with visualization of the explored search-space. As illustrated in the captured instance of Fig. 3a, upon detection of each tangible, the developed TUI approach provided visual feedback to students by projecting a color-coded square around each tangible, digitally interlinking the objects with the interface.

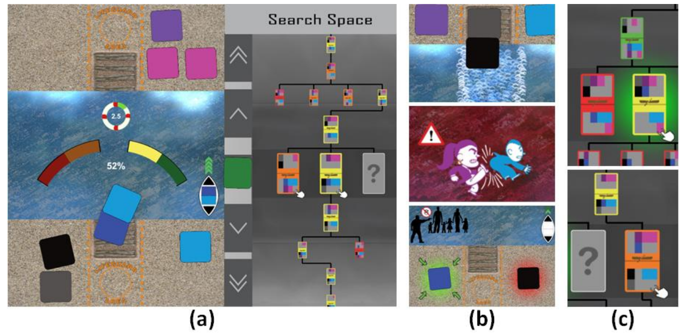

Fig. 3. Developed graphical interactions to aid in search-space exploration: a) Graphical interface layout with game section showing river crossing puzzle on right and explored search-space visualization area on left, b) Interactive graphical animations to cue users on underlying concepts, c) Search-space visualizations graphics reflecting state information.

Throughout the execution of search-space exploration via the river-crossing puzzle, the proposed tangible approach integrated numerous visual animations to aid students in progressing through their solutions. As illustrated in Fig. 3b, a variety of digital imagery and animations are timely projected to provide students indications on the validity of their actions in light of the puzzle constraints. This interactive feedback is perceptually coupled in the proximity of respective tangibles, providing an augmented understanding of the collaborative actions and decisions performed. These graphical representations were carefully designed to provide intuitive formative feedback to students, which instinctively led students to further engage in an active experimental learning pedagogy.

Interlaced with the challenging gamified aspect of the puzzle, the tangible approach integrates the educational aspects of search-space conceptualization by multiplexing the tangible and digital interactions. Once students undertake a particular state-change selection by physically placing characters within the raft, a digital confidence dial is projected adjacent to the docked raft as shown in Fig. 3a. This circular digital dial prompts users to rotate the raft by physically pointing the tangible towards the selected colored range. This manipulation presents the proposed TUI approach the ability to allow students to collaboratively determine their confidence-value considered search-state which is recorded by the system. This interaction instinctively prompts students in collaborative interaction and discussion of the search-space validity and understanding.

Moreover, following the consideration of a search-state, the TUI system populates the left section of the interactive surface, illustrated in Fig. 3a, with a graphical visualization of the explored search-space. Using color-coded depictions in relation to the confidence-value chosen, as shown in Fig. 3c, the TUI framework coherently interlinks the character state information using associatively colored icons. Each state is appropriately displayed in the ply of the explored search-space solution and can be navigated through a scrolling approach via the magnifier tangible. As shown in Fig. 3a, tangibly navigating through the selection of vertical navigational buttons allows students to zoom into previously explored plies whilst retaining an understanding of the entire search space. This provides learners with the ability to further concretize their understanding of the explored search-space whilst also providing the ability to implement search-space concepts such as backtracking. This functionality is tangibly implemented by providing students with the ability to physically select a previously transitioned state using the magnifying tangible. Digitally, the system would revert to the selected state and indicate to students the tangibles changes needed using graphical cues as shown in Fig. 3b. The developed tangible approach thus enabled HEI students to interactively explore a complex search-space problem using embodied interaction whilst coverging to the puzzle's solution.

IV. Evaluation Methodology

The experimental evaluation methodology was designed to provide a quantitative analysis of the effectiveness and suitability of the proposed tangible approach to aid conceptual understanding of search-spaces in higher education. More specifically, the intended design aimed to objectively compare the students' knowledge gain following an experimental session using the described tangible approach against that obtained using current search-space GUI-based educational software. This was measured using both open-ended examinations on theoretical and practical concepts of search-spaces as well as a student interaction log which programmatically monitored and assessed the students' exploration of search-spaces whilst solving a problem-based context. To this end, the sequential flow of the evaluation methodology is outlined in Fig. 4, together with the lecturing and assessment design.

In accordance with this design, evaluation sessions were undertaken at Middlesex University Malta, with final-year undergraduate students studying Computer Science and Information Technology. Participants were chosen using a convenience sampling from enrolled students within an Artificial Intelligence module. 48 students volunteered for this study, which ranged between the age of 19 to 31, and the evaluation session was aptly scheduled to coincide with the curriculum delivery of the search-spaces concepts within AI lectures. To mitigate the potential bias introduced from prior study or work experience from students on search-spaces, a differential evaluation methodology was adopted [7], [21]. Hence, to obtain an individualistic baseline for eventual assessment of knowledge gain within participants, a pre-session examination on conceptual search-space knowledge was undertaken by all students prior to tuition.

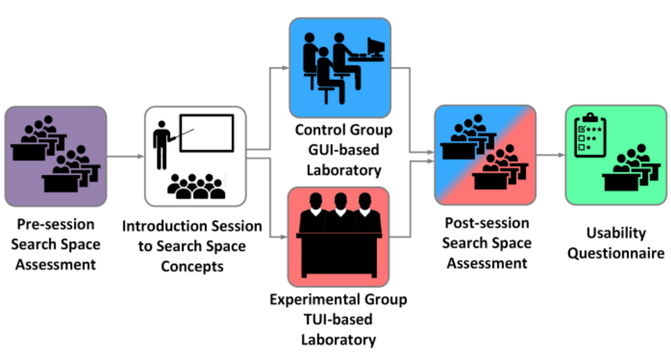

Fig. 4. Evaluation stages designed for assessing the suitability of educational approaches for search-space concepts.

Adopting a seminar/laboratory approach for tuition, the students were randomly split into groups of six and undertook a short introduction to the concepts of search-space exploration as well as given instruction on the aim and rules of the investigated river-crossing problem. To ensure uniformity and reduce experimental variables, this traditional lecture was conducted by the same lecturer for each group and a set of identical slides used to ensure the same content delivery is provided in each session.

As illustrated in Fig. 4, students were subsequently randomly split into two groups of three students which constituted the experimental and control groups for the laboratory assessment. The intended design variable within the evaluation methodology was to utilize a different educational technology. Thus, whilst the experimental cohort explored the search-space of solving the *Japanese family river-crossing* puzzle via the proposed tangible approach, the control group utilized a web-based educational software for an identical puzzle which is optimized for GUI-based interaction [37]. The latter were also provided with additional laptops as well as pen-and-paper facilities to record and analyze search-space states whilst exploring. This ensured that both cohorts had equal ability to derive and evaluate the search-space for the contextual problem.

Following a 20-minute laboratory session, both groups were once more assessed with a set of open-ended examination questions, which covered the same theoretical and practical knowledge as the pre-test assessment but adopted different questions to mitigate influential-bias from the prior assessment.

V. Results and Discussion

The examination questions were assessed against pre-defined marking schemes and grades were correlated for each individual student making use of unique student identification. The performance of each cohort was subsequently averaged and tabulated in Table 1. Analyzed under an independent sample t-test, the pre-test grades showed no significant statistical difference (*p-value*>0.23) between control and experimental group of students outlining the suitability of the randomized allocation methodology.

Table 1: Assessment Grade Analysis

	Assessment Grades				
	Pre-Session	*Post-Session*		*Knowledge Gain*	
	All	*GUI*	*TUI*	*GUI*	*TUI*
mean (μ)	10.9%	46.7%	85.1%	38.1%	71.9%
std dev (σ)	13.5%	18.9%	11.0%	17.5%	14.3%
Sample Size (N)	48	24	24	24	24

	Knowledge Gain Difference				
	Mean (μ)	*Std Dev (σ)*	*p-value*	*test statistic*	*DoF*
Paired t-Test	33.8%	20.3%	0.0001	8.32	24

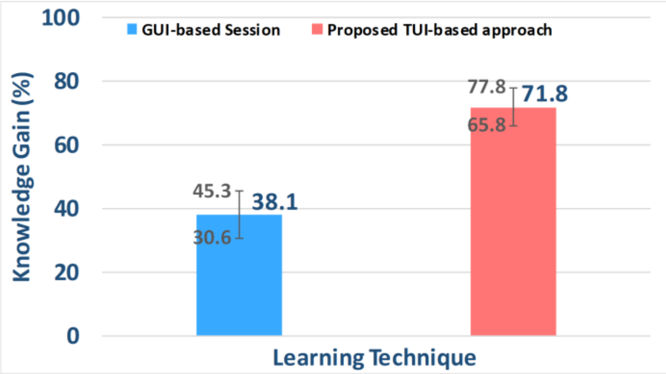

Fig. 5. Relative grade improvement obtained by students with 95% confidence levels following both educational sessions respectively.

As can be visualized from Fig. 5, control group students who engaged with the web-based GUI software obtained a knowledge gain of 38.1% (σ: 17.5) when comparative grades are analyzed under a paired sample t-test at a 95% confidence level (*p-value* < 0.001). In contrast, the experimental group students who undertook the same search-space exploration puzzle obtained significantly higher grades as listed in Table 1. Thus, the proposed tangible approach provided students with an average knowledge gain of 71.8% (σ: 14.2, *p-value* <0.001), illustrated in Fig. 5. As detailed in Table 1, the improved conceptual understanding of search-space exploration principles brought about by the proposed tangible educative approach was confirmed using an independent sample t-test on the individual knowledge gain grade differences which highlighted the statistical difference of the 33.8% (σ: 20.3) improvement (*p-value* <0.001).

Analysis of the search-space exploration done by each group of students further outlined that the experimental students evaluated a wider search-space coverage through the TUI framework in comparison to the control group. The exploration data was statistically analysed using a Welch two-sample t-test, which compensated for the sample sizes and adjusted the degrees of freedom accordingly. The results highlight, at a 95% confidence statistic (*p-value* <0.001) that the experimental group undertook an average search-space coverage of 8.1% (σ: 1.7) in contrast to the 3.3% (σ: 1.3) done by the control group. The extent of this search difference was outlined by an estimated effect size (Cohen's *d*) of 2.85, yielding a confidence power value of 99.8% for the observed effect. The significance of the t-test power value outlines the probability of observing a real effect from the given data.

To ascertain the meaningfulness of this additional search-space exploration by TUI-based interaction, every individual action and state investigated by students were analyzed from the logged data. The proposed hypothesis investigated H_1, was therefore that a more meaningful exploration was undertaken through the tangible approach constituting of a mixture of breadth-first search and depth-first search methodologies through the state-space. To quantitatively evaluate this hypothesis, a direct comparison was undertaken for the sequential actions of each student group as visually aggregated in Fig. 6.

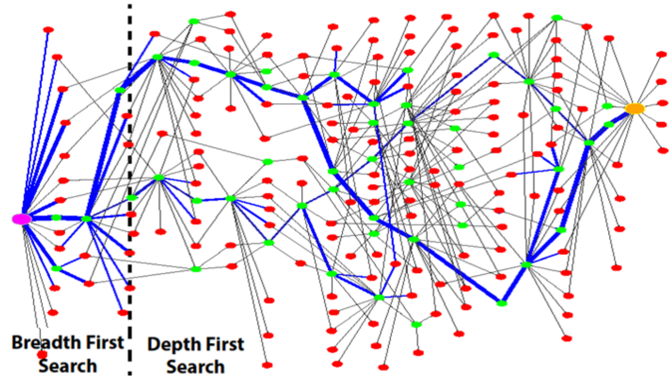

Fig. 6 Search-space exploration undertaken by TUI-based interaction (blue edges). Edge thickness indicates the number of students exploring that path. Start node is shown in pink, valid states in green, invalid states in red, and the goal state is depicted in yellow.

The comparison was computed against a random/blind search approach, which, simulated through a hill-climb algorithm, considered each action based on the next best available state change using a heuristic derived from the number of persons transported across the river to score each state [44]. At each time instant, the selected students' moves were algorithmically compared to a hill-climb approach over a short time-window of the next 10 moves, and the path similarities were measured using the Levenshtein distance metric. A two-sample Kolmogorov-Smirnov test was performed to test the proposed hypothesis, obtaining a test statistic of D=0.2 at 95% confidence level (*p-value* < 0.001), thus disproving the H_0 null-hypothesis. This result underlined the meaningful interaction and exploration undertaken through the TUI system, which as shown in Fig. 6., visually illustrates that a broad breadth-first search was largely undertaken by students prior to subsequently selecting a depth-first search towards the solution.

VI. Conclusion

In contrast to prior work in teaching complex and abstract concepts in HEIs, this paper presents the adaption of a tangible approach to further engage students in active learning. Aimed at aiding the conceptual teaching and learning of AI state-space exploration to HEI students, the paper details the design and development of a TUI-based educational approach. An evaluation methodology was designed and implemented to assess the effectiveness of the proposed tangible approach in augmenting students' ability to apply their acquired knowledge within a problem-solving puzzle. The intended learning outcomes were analyzed using both appropriately structured examination questions and interaction logs to derive a statistical understanding of the search-space exploration. The significant findings of this paper highlight the knowledge gain acquired by students interacting with the proposed tangible approach hence outlining the aptness for suitably designed TUI frameworks to be implemented within HEI contexts. Furthermore, the capabilities derived from the investigated methodology in higher education highlights the potential of tangible educational technology to aid in teaching and learning of complex and abstract notions.

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