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User friendly haptic tool for soccer fans with vision disabilities: Design and proof of concept

ABSTRACT

Loss of eyesight inflicts multiple difficulties in everyday lives' tasks affecting not just the visually impaired but also their loved ones. The sense of being depleted by the otherwise visually perceived satisfaction from attending various events becomes a burden not just in terms of joy but also in relation to accompanying parties. The aim of this research work was to provide a worthy perceived experience of attending a soccer match with the company of a friend, centered at the visually impaired person's needs and perspective. The methodology developed was based on a holistic approach combining a number of creative tools, in order to explore, visualize and evaluate the proposed solutions, with advanced CAD modeling, rendering techniques and 3D printing technology for improved representation and prototyping of the final product. Evaluation via multi-criteria decision-making casted the developed system as quite usable, suitable for assisting the visually impaired users in absorbing valuable information regarding the real time progress of a live soccer event using the selves-developed tactile interface. That way, visually impaired people are able to use the final product with a great deal of success and "feel the view" and the "time" in a variety of cases, allowing them to better enjoy attending an entertainment event, such as soccer, with the interactive company of a friend.

KEY WORDS
Haptic tool, visually impaired people, CAD modeling, conceptual design, criteria based model design, 3D printing, soccer, AHP. Fuzzy SAW

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Introduction

Late advances in precision modeling enable the design and manufacture of physical haptic structures capable of translating and rendering visual representations to non-visual representations (Tobitani et al., 2021; Yao et al., 2020; Milos, Vujčić & Majnarić, 2021). Regarding the latter, in (Mc Gee et al., 2000) the authors identified possible effective combinations of haptic and live auditory textural information that exploit the sense of touch (haptic), the feeling of motion (kinesthetic) and the received force-feedback from the mechanical production of information sensed by the kinesthetic system, and the sense of pressure, temperature and pain felt by the skin (either cutaneous or tactile when focused upon pressure solely). These combinations indicate that it might be possible to take advantage of the sense of touch as an alternative means to that of sight for sending and receiving information.

Efforts have been made (Mordini et al., 2018; Mulloy et al., 2014; Brewser & Murray-Smith, 2001) to develop sensory substitution devices (SSDs) aiming to convert the stimuli normally accessed by a certain modality into appropriate stimuli suitable for being accessible by another sensory modality. The aim of such SSDs is to improve efficiency, effectiveness and satisfaction of the end user. Yet, resolving in arbitrary combinations of multimodal information of different senses has been proven to be rather ineffective (Gori et al., 2016) receiving low user acceptance rates and demonstrating virtually no adaptability regarding children's use. Some of the downsides of such high technology devices reported in the literature (Elmannai & Elleithy, 2017) include, but are not limited to, invasiveness of the proposed system, excessive cognitive load, absence of an action-perception link and simultaneous integration of multiple types of sensors.

Sensory substitution devices' requirements are likely to differ depending on the application and the specific impairment of the end user. Thus, it was deemed important (Hamam et al., 2008; Hayward & Astley, 1996) to evaluate the quality of experience of sensory substitution haptic devices throughout the various development stages to extract application-specific optimum design principles for tactile interaction (Challis, 2000). Included among others are touchable elements as reference points, organization of commands and functionalities as well as simplicity and usability of common functionalities (Chiti & Leporini, 2012).

The purpose of this research work is to assist the visually impaired in absorbing valuable information regarding the real time progress of a live soccer event using a selves-developed tactile interface by improving the quality of experience. The usability of the developed haptic tools is evaluated by combining Analytic Hierarchy Process and Fuzzy Simple Additive Weighting theory. AHP has been proved ideal for comparing the weights of criteria in several other evaluation experiments (Kabassi, 2021a; Kabassi,2021b) and the comparison of several multi-criteria decision making models (Kabassi, 2021a) such as SAW, WPM, TOPSIS, VIKOR, PROMETHEE II revealed that SAW is very robust and maintain partly the ranking of the alternatives even if the weights of the criteria change.

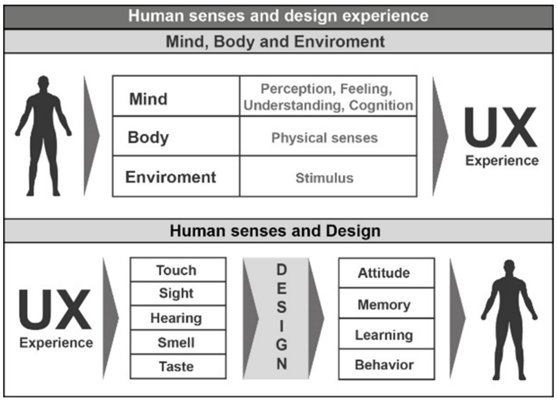
The criteria used for the evaluation of the usability of the system represent the main requirements for designing such interfaces. These criteria have been acquired by analyzing related papers on the field (Mc Gee et al., 2000; Haman et al., 2008; Gori et al., 2016; Challis et al., 2000) as well as other evaluation experiments (Kabassi et al., 2018; Kabassi & Maravelakis, 2015). High precision 3D modelling (Tobitani et al., 2021; Maravelakis et al., 2012; Maravelakis et al., 2014a; Maravelakis et al., 2014b; Axaridou et al., 2014) and printing (Wang et al., 2017) systems were encompassed for maintaining consistency of mapping in order to ensure the validity of the described actions in both the visual and the non-visual representations. Static tactile representations were selected to be asserted within the interface environment, as dynamic ones would have inflicted the difficulty of having to notify the user in real time where within the interface a change has occurred (Caspo, Wersenyi & Jeon, 2016). Also, height was mainly used rather than depth as the discriminating factor for the user to home-in on certain action tactile features, while the latter, i.e. depth, was selected for indicating and safely discriminating the dense faithful mapping of the football pitch layout within the penalty area on the high precision 3D model.

As analyzed thoroughly in the sections to follow, this research approach addresses several key deficiencies identified in the literature (Jia et al., 2013; Hasper et al., 2015), such as ease of use, natural engagement in terms of how close is the interaction to the real world, minimal invasiveness and need occupation of other senses, easy to comprehend, low cognitive load, minimal training requirements, constructive simplicity with faithful points, manageable size and weight, portability and most significantly general satisfaction as indicated by the end users themselves. In order to achieve the best possible level of satisfaction of the impaired user multi-criteria decision-making (MCDM) (Oprocovic & Tzeng, 2004) has been encompassed. Indeed, multi-criteria decision making models have been proved very successful in evaluating using expert knowledge the usability of a system (Adepoju et al., 2020; Bilalis et al., 2006; Konstantaras, 2013; Konstantaras, 2016).

An evaluation experiment depends on several and often conflicting criteria. MCDM techniques provide a flexible and transparent way to find solutions to such complex problems (Yiannis et al., 2020). Indeed, in order to aggregate the different criteria, different MCDM models have been developed. These models are being used before evaluating software for example, websites of cultural (Kabassi, Botonis & Karydis, 2020; Kabassi, Karydis & Botonis, 2020; Kabassi et al., 2019; Kabassi & Maravelakis, 2015) or environmental (Kabassi & Martinis, 2020; Kabassi, Martinis & Papadatou, 2019) content. The main advantage of multicriteria decision making methods in comparison with other methods and theories is that they provide a well-defined methodology for aggregating the values of the different criteria, which may have different weights of importance. Some MCDM models also have a well-defined way of calculating weights of importance for each criterion. This advantage makes MCDM methods preferable either for using solely or in comparison with other methods, such as fuzzy logic (Hamam et al., 2008; Liu & Wang, 2007; Maravelakis et al., 2006), soft-computing and deep learning (Kuo & Liang, 2012; Konstantaras et al., 2008; Konstantaras et al., 2021; Konstantaras, 2020). Different MCDM methods also provide different ways for combining the criteria. Therefore, an important decision while applying MCDM is selecting the method that best fits the needs of the problem being solved. For example, there are methods (Büyüközkan & Ifi, 2012) that implement pairwise comparisons (eg. VIKOR, TOPSIS), methods that calculate the linear combination of criteria (eg. SAW), etc.

Conceptual Design Methodology

The proposed holistic methodology targets the users' senses in order to offer a worthy perceived experience and is being successfully applied in other product design industries as well (Manavis et al., 2020; Manavis et al., 2021). It starts with an approach that contains many aspects of the users' experience focused from their perception and understanding point of view to their physical senses and environmental stimulus. The designer is forced to deal with an increasing number of issues when more and more senses are deployed in order to offer a worthy user-targeted experience. The senses are the basis for stimulating the user's attitude, memory, learning and behavior. As a result, users receive greater satisfaction from the product's usage (Figure 1). It is evident that a great deal of attention is given towards the social aspect of the user-centered approach, which traditionally does not get a great deal of attention from researchers and designers (Efkolidis et al., 2019).

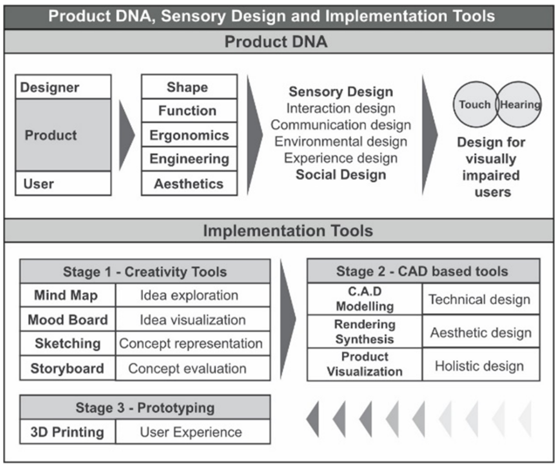


» **Figure 1:** *Designing the experience via human senses*

Figure 2 depicts a roadmap that leads both the designers and users in implementing an experience that can satisfy all segments of the product market. From both the designers' and the users' point of view, the product is generally perceived as the experience that contains a number of characteristics i.e. shape, function, ergonomics, engineering, aesthetics, while these lead to highlight each one of them, when using different design approaches i.e. sensory design, interaction design, social design. When the design is targeted for visually impaired users, the main focus is concentrated on sensory design and social design principles, that use to a greater extend the senses of touch and hearing.

There are three separate stages for which certain tools are used for successfully implementing the proposed methodology:

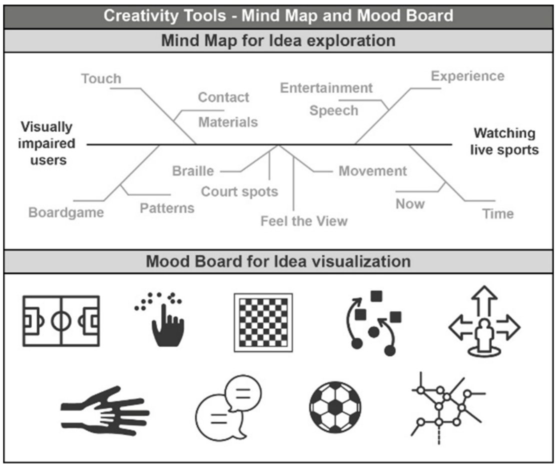
- a number of creativity tools are used to explore, visualize and evaluate the proposed solutions from the entire design space available. This means that more cases can be dealt with for a variety of products and demands.
- CAD models with advanced rendering techniques offer an almost realistic representation of the designed solution and satisfy the holistic targeted approach.
- 3D printing is the basis of prototyping and thus the user can very early in the design process experience its use and offer feedback via his/her opinion. This feedback that comes directly from the user, releases the design creativity towards directions, that offer multiple added value to the user. The prototype of the product is getting attention early in the design cycle and thus minimizes future design mistakes and corrections, affecting drastically the reduction of the development cost.



» **Figure 2:** *Roadmap for implementing the proposed methodology*

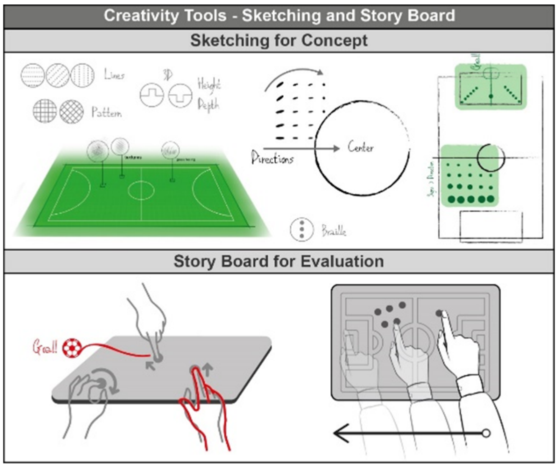
Both mind-map and mood-board tools were used in order to explore the design space and visually gather pieces of information and features, that can be incorporated later on the proposed product (Figure 3). The problem under consideration is the "live football watch experience of visually impaired users". The user needs to touch the product under consideration and listen, if possible, at the same time so as to understand the motion of the players and the position of the ball while the game unfolds.

Visually impaired people are well adapted to communication via the braille language so a similar technique would be easier to grasp and use. The board of the game should be built with patterns, thus leading/guiding the users when they touch the patterns in order to be able to immediately understand the area of the real-life football pitch where the players controlling the ball participate in. The rules of the game should be easily explained and transferred to the user in an intuitive way. The user should be able to experience the term “time” in a variety of options. That means that the sense of the real player being in a specific area in the real football pitch and the direction of the ball to another area should be easily transferred to the visually impaired person, the principle “feel the view” should be implemented via his/her senses. It is evident that a similar approach can be followed for other sports that could also become openly available to visually impaired users.



» **Figure 3:** *Exploring and visualizing design ideas*

The next step followed was the extensive use of sketches (Figure 4). A number of different patterns were incorporated. Basic and easy to touch geometries offered ease of understanding the general football pitch layout. Then smaller patterns are used around the center of the football pitch for offering the experience of stepping away from the center. Smaller or larger line patterns together with their inclination offer the possibility to recognize the position of the player from the center and his direction of motion. The same applies when using the same idea in the area of the goalpost. Then with the use of the gameboard the way of successful implementation is presented. In this case, the presence of the user assistant is revealed and his role is highlighted. The assistant will guide the finger of the visually impaired person at the appropriate position in the gameboard in accordance to the actual position of the player controlling the ball on the football pitch, while at the same time will be able to describe how the game is evolving. It is at this moment that both senses (touch and hearing) unite their inputs for assisting the user to completely understand the evolution of the game in real time.



» **Figure 4:** *Sketching and visually evaluating the design proposal*

Finally, a Computer-Aided Design (CAD) based model was used for addressing all the previous concepts and provide access to a 3D solid model. The 3D solid model was used for acquiring a 3D printed gameboard to be used for testing the users’ experience following the holistic design process and approach (Kyratsis, 2020; Kyratsis, Kakoulis & Markopoulos, 2020). The CAD model is actually a gameboard that was used by the visually impaired user, while the assistant was leading the user’s finger and described in real time, the evolution of the game (Figure 5). In such a way, the user was able to understand the position and motion of both the active players and the ball at the same time as the game unfolded.

» **Figure 5:** *3D printing-based prototype used during live game*

Criteria-based Model Design

The proposed approach introduces a tailor-made model design of a football pitch encompassing action zones suitably constructed to meet specific criteria (Ardévol, 2013) categorized as design assessment, reality approach and user experience, outlined below:

A) Design Assessment (DA)

- Orientation (DA_0). Does the model have clear touchpoints for the initial orientation?

- Size (DA_1). Do you need to overreach in order to discover the full extent of the haptic model?
- Height as a filtering Mechanism (DA_2). How go the different heights on the model help you recognize and discriminate different areas of the field?
- Level of “empty space” Areas (DA_3). Are there areas on the haptic model that cannot be easily interpreted?
- Faithful touchpoints (DA_4): How natural is the change between touchpoints on the haptic model?
- Perceived Roughness (DA_5). How physical roughness facilitates the interaction with the model?

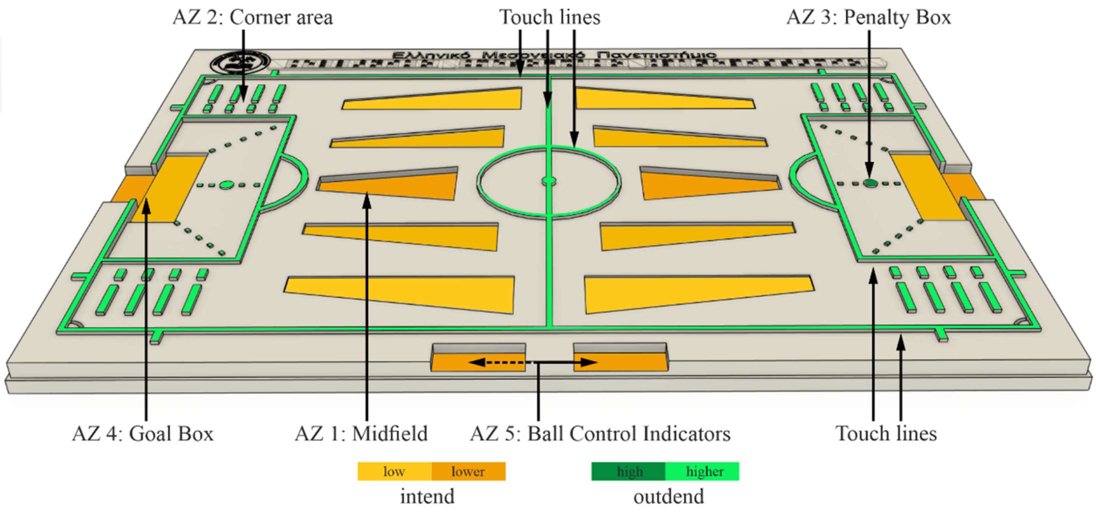
B) Reality Approach (RA)

- Natural engagement (RA_0): How close do you think is the interaction to the real world?
- Multisensory integration (Acoustic & Touch) (RA_1). How well acoustic senses are intergraded into the haptic model?
- Consistency of Mapping (RA_2) Do you think that there is a consistency between different touchpoints on the haptic model?

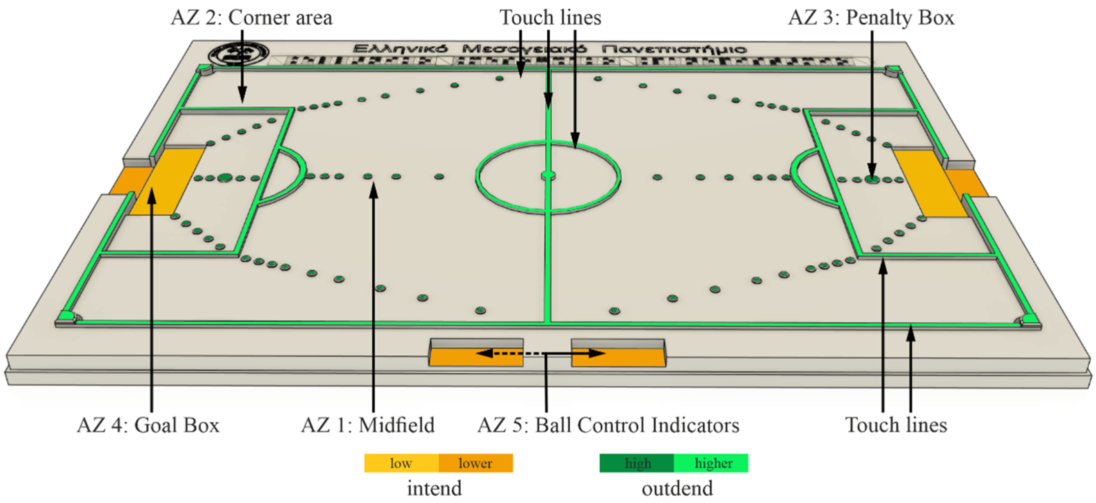
C) User Experience (UX)

- Invasiveness (UX_0). How free do you feel by using the haptic model?
- The natural expression of action (UX_1): does the model allow you to act naturally?
- Cognitive Load (UX_2). How much attention is required for using the haptic model?
- Training Effort Required (UX_3). How much training is required in order to start using the model?
- Level of Satisfaction (UX_4): How satisfied does the user feels from his/her experience with the system?

For the model to satisfy the aforementioned criteria it was deemed necessary to clearly discriminate between field touchlines and action zones.



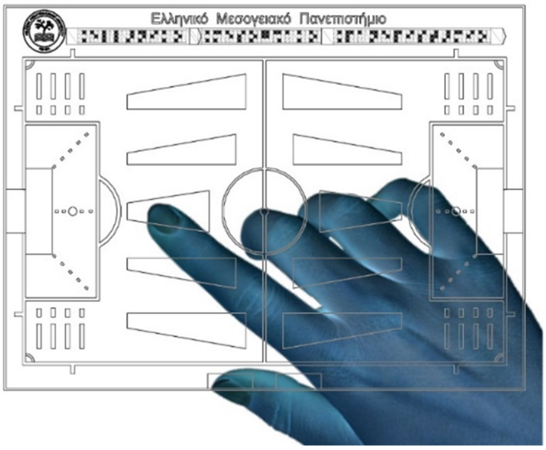
a) Design A



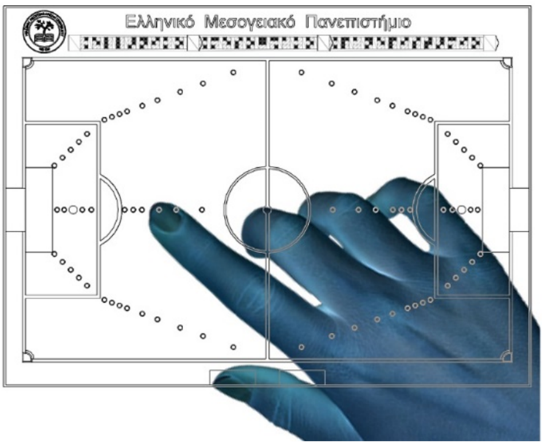
b) Design B

» **Figure 6:** *3D models of the football gameboards*

In terms of the former, all touchlines have been printed outdented as continuous lines for it is easier to detect by touch, follow along and quicker to realize which is which (side touchline, goal line, halfway line, center circle, penalty box, penalty arc, goal box) in terms of positioning. The dimensions of the field can be tailor-maid to the user's hands in such a manner to single-handedly be able to reach from one goal line to the center of the football pitch. This enables to user to receive full haptic input of the gameplay on either side of the field and be clear at any time on which team is pressing forward and who is defending. The shortest distance between the touchlines (Figure 6a Touchlines), i.e. that of the goal box and the goal line is made certain to fit in the full width of the user's pointer finger, and based on that the entire football pitch touchlines are printed to scale in analogy to the actual football pitch. Furthermore, special care has been taken to ensure that there are no empty areas significantly larger than the tip of the pointer-finger in order to enhance the real-time continuous haptic interpretation of the model while game-play unfolds.



a) *Design A*



b) *Design B*

» **Figure 7:** *Haptic use of the 3D football gameboard models*

Regarding the latter, initially all action zones (Fig 6a, AZ1-4) were designed intended to easily discriminate from touchlines. This approach proved efficient in wide open-spaced areas among the touchlines such as the action zones (Figure 6a. AZ1) amidst the halfway line and the penalty box and arc areas. The available spacing in these two areas on either half of the football pitch enabled the inward extrusion of five parallel action zones that start wide near the middle of the football pitch and narrow-in while approaching the penalty box. Narrowing occurs from one side of the action zone corresponding to the actual side of play in the football game with the exception of central advancement action zone in line with the central circle and goal area where both sides of the action zone lean inwards. Also, the depth of these action zones reduces while leaning towards the sides of the football pitch.

These cultivations to the model were possible as the available spacing was enough to fit an adult's finger to either of the aforementioned action zones. This is not the case though when the game-play unfolds on either side, left or right, of the penalty boxes (Figure 6a, AZ2). In those areas the available spacing is limited and a better haptic perception was received for pairs of parallel outdented lines, four pairs in each penalty box side, with the innermost action lines set to one third of the length cast to the outward action lines.

Once game-play proceeds into the penalty box touch lines (Figure 6a, AZ3), this is being immediately haptically perceived by a sudden drop in the field depth. Also, to further assist with the ease of haptic awareness of the direction of play within the penalty box, three outdented dotted lines have been printed; between the two in field right angles of the penalty box and the two equivalent points of the goal box as well as a vertical dotted one running through the penalty spot expanding right in the center in between the penalty and goal boxes. The penalty spot itself is printed as an exaggerated circular limp rather than a dot sized mark of the latter action line.

Once in the goal box (Figure 6a, AZ4) a further increase in depth is haptically sensed nicely trapping the user's finger into it, enabling it to comfortably move sidewise and sense the goal line. Outside the goalpost, the goal line is as a wall whose height reduces when moving from the goal box to the penalty and from the penalty box to either near the corner-kick area.

The goal-line within the goalposts is sensed by yet another increase in depth, and with a slight side-twitch of the finger the user can feel just one of the aforementioned picky wall corners corresponding to the two vertical goalposts enabling the user to realize at which side of the net a goal was scored. Missed goal efforts that ended up outside the goalposts are being perceived by guiding the user's finger over the goal-line wall extending outside the left or right goalpost within the goal area.

If a corner kick is awarded the finger is guided to the corner area where the corner mark can be haptically sensed intended. In case of a free-kick, the equivalent touchpoint is either of the two in-filed corners of the goal box. In the event of a goal being scored the finger is directed to the exaggeratedly outdented kick-off spot in the center of the halfway line crossing the center circle.

Just outside the sideline and on either side of the football pitch the benches of the two teams are printed by being intended (Figure 6a, AZ5). The purpose is for a second finger, most suitably the thump, to be used for sensing one of the benches at any time depending on which team has control of the ball at any given instance. Finally, near the corners and outside the sidelines and the goal-lines outdented markers have been placed to indicate proximity to the corner area.

The prototype in Figure 6a was then tested early in the design process by two types of visually impaired users, users that were born blind or lost their eyesight during infancy and users that had lost their eyesight later on in their lives. From the received feedback, the former group stated that they were happy with the compactness of action zones amongst football pitch lines as it felt easier for them to absorb haptic information while they had their finger moving upon the 3D football pitch model by their guide. On the other hand, the latter group of users that had the opportunity to visually sense and remember a football pitch during gaming action stated that they would prefer a greater degree of empty space amongst football pitch lines. The greater degree of freedom apparently lessens the rate and effort in absorbing haptic information while their fingers were guided upon the 3D football pitch model. The possible expected loss of tactile orientation when crossing larger empty spacings appears to have been compensated by the former knowledge of actual football pitch layouts and unfolding football games.

These early design stage observations encouraged the authors to yet another design shown in Figure 6b targeted at people that were not visually impaired throughout their lives. This design includes fewer action zones in terms of numbers but also the dimensions of each action zone have been narrowed down to dotted lines to provide the additional increment in empty spacing as was suggested by the users. To account for proximity to penalty areas, the dotted lines were designed to be denser there and narrower towards the center of the football pitch. Haptic use of both 3D football gameboard models is shown in Figure 7a and Figure 7b, respectively, with both the hand and football gameboard model being plotted to scale with respect to their actual physical dimensions.

Evaluation: Applying Analytic Hierarchy Process for Calculation of the Weights of the Criteria

In order to evaluate the usability of the proposed system an evaluation experiment was performed. In the past, a quite different approach of combining usability evaluation with fuzzy MCDM (Büyüközkan et al., 2012; Chou, Chang & Shen, 2008) theories have been proposed. More specifically, the Fuzzy Simple Additive Weighting theory (FSAW) (Chou et al., 2008) has been combined with the framework for usability evaluation of virtual environments proposed by Sutcliffe & Gault (2004) for performing usability evaluation of Virtual Reality (VR) environments. In this paper, we show how Analytic Hierarchy Process (AHP) (Saaty, 1980) can be combined with FSAW for evaluating the usability of a Haptic Tool for Soccer Fans with Vision Disabilities. AHP is one of the most popular MCDM theories. AHP aims to analyze a qualitative problem through a quantitative method. This method uses the nine-point scale developed by (Saaty, 1980) for the evaluation of the goal with the criterion as well as the criterion with the alternative (Mulubrhan, Akmar Mokhtar & Muhammad, 2014).

Steps of the AHP theory were followed as given by (Zhu & Buchman, 2000): 1) Developing a goal hierarchy, 2) Setting up a pairwise comparison matrix of criteria, 3) Calculating the weights of the criteria. Taking into account these steps, the steps for implementing the theory are:

- **Developing a goal hierarchy**, which involves:
    1. **Forming the overall goal:** The overall goal is to evaluate the Haptic Tool for Soccer Fans with Vision Disabilities
    2. **Forming the set of criteria:** In this step the set of design criteria is being used.

- **Setting up a pairwise comparison matrix of criteria:** In this step a comparison is implemented among the criteria of the same level. For this purpose, the set of three (3) human experts who acted as decision-makers were asked to make the pairwise comparisons of criteria. The group of human experts was formed by two experts in usability and one expert in software for people with vision disabilities. The decision makers agreed on the values presented in the tables below.

One table was completed for the pairwise comparison of the criteria of the first level (Table 1), one for the sub-criteria of Design Assessment (Table 2), one for the sub-criteria of Reality Approach (Table 3), and one for the sub-criteria of User Experience (Table 4).

Table 1

Pairwise comparison of the criteria of the first level

	DA	RA	UX
DA	1	0.50	0.20
RA	2	1	0.33
UX	5	3	1

Table 2

Pairwise comparison of the sub-criteria of Design Assessment

	DA_0	DA_1	DA_2	DA_3	DA_4	DA_5
DA_0	1.00	1.00	0.50	0.33	0.20	2.00
DA_1	1.00	1.00	2.00	1.00	2.00	3.00
DA_2	2.00	0.50	1.00	0.50	0.50	2.00
DA_3	3.00	1.00	2.00	1.00	0.50	1.00
DA_4	5.00	0.50	2.00	2.00	1.00	1.00
DA_5	0.50	0.33	0.50	1.00	1.00	1.00

Table 3

Pairwise comparison of the sub-criteria of Reality Approach

	RA_0	RA_1	RA_2
RA_0	1	1	2
RA_1	1	1	2
RA_2	0.5	0.5	1

Table 4

Pairwise comparison of the sub-criteria of User Experience

	UX_0	UX_1	UX_2	UX_3	UX_4
UX_0	1.00	3.00	1.00	7.00	0.13
UX_1	0.33	1.00	0.33	2.00	0.17
UX_2	1.00	3.00	1.00	5.00	0.50
UX_3	0.14	0.50	0.20	1.00	0.11
UX_4	8.00	6.00	2.00	9.00	1.00

- **Calculating weights of criteria:** After making pairwise comparisons between the criteria of the same level or the sub-criteria of the same criterion, estimations are made that result in the final set of weights of the criteria. For this purpose, the principal eigenvalue and the corresponding normalized right eigenvector of the comparison matrix that is calculated, provide the relative importance of the various criteria being compared. The elements of the normalized eigenvector are now the weights of criteria or sub-criteria. In terms of simplicity, we had used the 'Priority Estimation Tool' (PriEst) (Sirah, et al., 2015), an open-source decision-making software that implements AHP, for making the calculations that the theory requires. This process resulted in the following weights for the criteria and the sub-criteria:

A) <u>Design Assessment (DA)→</u> w_{DA} = 0.122

- Orientation (DA_0)→ $w_{DA\,0}$ = 0.100
- Size (DA_1) → $w_{DA\,1}$ = 0.238
- Height as a filtering Mechanism (DA_2) → $w_{DA\,2}$ = 0.140
- Level of “empty space” Areas (DA_3) → $w_{DA\,3}$ = 0.189
- Faithful touchpoints (DA_4) → $w_{DA\,4}$ = 0.230
- Perceived Roughness (DA_5) → $w_{DA\,5}$ = 0.104

B) <u>Reality Approach (RA)→</u> w_{RA} = 0.230

- Natural engagement (RA_0) → $w_{RA\,0}$ = 0.400
- Multisensory integration (Acoustic & Touch) (RA_1) → $w_{RA\,1}$ = 0.400
- Consistency of Mapping (RA_2) → $w_{RA\,2}$ = 0.200

C) <u>User Experience (UX)→</u> w_{UE} = 0.648

- Invasiveness (UX_0) → $w_{UE\,0}$ = 0.170
- The natural expression of action (UX_1) → $w_{UE\,1}$ = 0.070
- Cognitive Load (UX_2) → $w_{UE\,2}$ = 0.200
- Training Effort Required (UX_3) → $w_{UE\,3}$ = 0.040
- Level of Satisfaction (UX_4) → $w_{UE\,4}$ = 0.170

One can easily observe that the criterion ‘User Experience’ is much more important than the other two criteria. As far as ‘Design Assessment’ is concerned the criteria ‘Size’ and the ‘Faithful touchpoints’ are considered more important than all the others. Regarding the criterion ‘Reality Approach’ the two sub-criteria ‘Natural engagement’ and ‘Multisensory integration’ are equally important and have higher weight of importance than ‘Consistency of Mapping’. The ‘Cognitive Load’, the ‘Invasiveness’ and the ‘Level of satisfaction’ are the most important sub-criteria of the criterion ‘User Experience’, that is considered the most important of all.

Evaluation: Applying FSAW for the implementation of the main experiment

The main evaluation experiment involves the participation of real users, interacting with the tool and answering the questions that correspond to each criterion.

Since AHP performs pairwise comparisons between the alternatives being evaluated and, in this case, there is only one alternative, and a crisp value for the tool being evaluated should be calculated, we combine AHP with FSAW. Fuzzy SAW has been selected because it is easier for users to provide linguistic terms to criteria rather than arithmetic values.

Fuzzy SAW is applied as soon as the weights of importance of all criteria have been calculated. For this purpose, the following steps are implemented:

1. **Forming the set of the tool's evaluators.** This group may involve real users of the tool and/or design experts in software usability for all. More specifically, thirteen nearly fully impaired users from various football club associations cooperated in this research work. Out of the thirteen overall users, four of them were born blind and the nine users had gradually lost their eyesight at various aging stages in their lives.
2. **Assigning values to the criteria.** In order to make this process easier for the users, especially for those that do not have experience in multi-criteria analysis, the users could use linguistic terms for characterizing the fourteen criteria presented at the beginning of this section. The answers to these questions are linguistic terms and show successful each criterion is fulfilled. The linguistic terms are: Very Poor, Poor, Fair, Good, Very Good. All criteria are assigned fuzzy values. This process resulted in Table 5.
3. **Linguistic terms are transformed into fuzzy numbers.** Each linguistic term is assigned to a fuzzy number, which is a vector $\tilde{a} = (a_1, a_2, a_3)$. The matches are presented in Table 6 (Chen 2000).
4. **Aggregating the values of the different evaluators (decision makers).** Each criterion should have at the end only one fuzzy number. For this purpose, the arithmetic mean is used. The arithmetic mean values of two fuzzy numbers $\tilde{a} = (a_1, a_2, a_3)$ and $\tilde{b} = (b_1, b_2, b_3)$ is calculated as follows:

$$\tilde{c} = \left(\frac{a_1+b_1}{2}, \frac{a_2+b_2}{2}, \frac{a_3+b_3}{2}\right) \qquad (1)$$

This process results in a triangular number for each criterion in the following Table 7.

5. **Calculating the weighted normalized fuzzy number.** In order to derive a fuzzy score for the system, the values of the criteria are multiplied with the corresponding weights (Equation 2).
   $\tilde{f}_{saw}$ is calculated using (2) as a fuzzy number. In order to evaluate the successfulness of the system one can either find which fuzzy number is closer to the value of $\tilde{f}_{saw}$ or calculate a crisp value. The above estimations revealed that the final value for the evaluation of the system is $\tilde{f}_{saw}$ = (4.98,6.15,6.83). This value is between the fuzzy numbers of 'Fair' and 'Good', which reveals that the system is acceptable but needs some improvements.

$$\tilde{f}_{saw} = w_{DA} \cdot \sum_{i=0}^{5} \widetilde{DA\_\iota} \cdot w_{DA\_i} + w_{RA} \cdot \sum_{i=0}^{2} \widetilde{RA\_\iota} \cdot w_{RA\_i} + w_{UE} \cdot \sum_{i=0}^{4} \widetilde{UE\_\iota} \cdot w_{UE\_i} \qquad (2)$$

Table 5
Values of the criteria

	DA_0	DA_1	DA_2	DA_3	DA_4	DA_5	RA_0	RA_1	RA_2	UX_0	UX_1	UX_2	UX_3	UX_4
user 1	Very Good	Good	Very Good	Fair	Very Good	Good	Good	Good	Very Good	Very Good	Fair	Good	Very Good	Very Good
user 2	Good	Very Good	Very Good	Poor	Good	Fair	Good	Very Good	Good	Fair	Good	Fair	Good	Good
user 3	Very Good	Very Good	Very Good	Fair	Very Good	Poor	Fair	Very Good	Fair	Good	Good	Poor	Very Good	Very Good
user 4	Good	Very Good	Very Good	Good	Very Good	Very Good	Very Good	Very Good	Very Good	Fair	Good	Fair	Very Good	Good
user 5	Very Good	Good	Very Good	Poor	Very Good	Very Poor	Fair	Very Good	Good	Very Good	Fair	Fair	Very Good	Very Good
user 6	Very Good	Very Good	Very Good	Good	Good	Good	Very Good	Very Good	Fair	Poor	Very Good	Good	Very Good	Very Good
user 7	Very Good	Very Good	Good	Very Good	Good	Poor	Good	Very Good	Good	Very Good	Very Good	Fair	Very Good	Very Good
user 8	Good	Very Good	Very Good	Fair	Good	Good	Good	Good	Fair	Very Good	Fair	Very Good	Good	Good
user 9	Good	Good	Very Good	Poor	Very Good	Very Good	Fair	Very Good	Good	Fair	Very Good	Fair	Good	Very Good
user 10	Poor	Fair	Good	Fair	Very Good	Poor	Very Poor	Good	Fair	Good	Poor	Poor	Fair	Fair
user 11	Very Good	Very Good	Very Good	Fair	Good	Fair	Good	Very Good	Very Good	Poor	Good	Very Good	Very Good	Very Good
user 12	Very Good	Very Good	Good	Good	Good	Good	Good	Very Good	Good	Very Good	Good	Fair	Good	Good
user 13	Very Good	Very Good	Very Good	Good	Very Good	Good	Fair	Good	Good	Good	Very Good	Good	Very Good	Very Good

Table 6

Linguistic variables and fuzzy numbers

Linguistic term	Fuzzy number
Very Poor	(0,0,1)
Poor	(0,1,3)
Fair	(3,5,7)
Good	(7,9,10)
Very Good	(9,10,10)

Table 7

Fuzzy numbers of the criteria

DA_0	(7.69,9.00,9.46)
DA_1	(8.08,9.38,9.77)
DA_2	(8.54,9.77,10.0)
DA_3	(4.00,5.69,7.23)
DA_4	(8.08,9.54,10.0)
DA_5	(4.54,6.00,7.23)
RA_0	(5.54,7.23,8.38)
RA_1	(8.38,9.69,10.0)
RA_2	(6.23,8.00,9.08)
UX_0	(5.77,7.23,8.23)
UX_1	(6.15,7.77,8.77)
UX_2	(4.38,6.08,7.54)
UX_3	(7.92,9.31,9.77)
UX_4	(7.92,9.31,9.77)

6. **Compute a crisp value.** A value is calculated for a system using a defuzzification method. Four defuzzification methods are most commonly used: the centroid method, mean of maximal (MOM), a-cut method and signed distance method (Zhao & Govind, 1991; Yager & Filev, 1994; Tsaur et al., 1997; Tang et al., 1999; Yao & Wu, 2000; Chou et al., 2008). All these methods share advantages and disadvantages (Klic & Yan, 1995), but Yao & Chiang (2003) propose the signed distance method, which is also used by Chou et al. (2008) in fuzzy SAW. The crisp total scores of individual locations are calculated by the following defuzzification equation:

$$d(\tilde{f}_i)=\frac{1}{3}(a_i+b_i+c_i),\ i=1,2,\ldots,m \qquad (3)$$

where $d(\tilde{f}_i)$ gives the defuzzified value (crisp value) of the total fuzzy score of the system being evaluated. The closer the value is to 10 the more usable the system is. The defuzzified value is calculated as follows:

$$d(\tilde{f}_{saw}) = \frac{1}{3}(4.98 + 6.15 + 6.83) = 5.99 \qquad (4)$$

A mediocre system would have a value of 5. Since the value of $d(\tilde{f}_{saw})$ is around 6, the defuzzified value confirms the evaluation of the system using a fuzzy number. The fuzzy number calculated in the previous step to evaluate the system was estimated between 'Fair' and 'Good'. As a result, the system is rated as 'Medium Good'.

Discussion and Conclusions

This research work was targeted to assist visually impaired people in absorbing valuable information during the real-time progress of a live football match using a selves-developed tactile interface. To achieve that, high precision 3D modelling and printing systems were deployed for pitch mapping consistency so as to ensure the validity of both the verbally described and the tactile actions performed upon it simultaneously. Static tactile representations were selected to be asserted within the interface environment and height was mostly used, rather than depth, as the discriminating factor for the user to home-in on certain action tactile features. The latter, though, was favored for indicating and safely discriminating the significantly denser faithful mappings of the football pitch layout within both penalty areas of the high precision 3D model.

The methodology followed in this research was based on a holistic approach. It combined a number of creative tools, in order to explore, visualize and evaluate the proposed solutions, with advanced CAD modeling, rendering techniques, and 3D printing technology for improved representation and prototyping of the final product. The aim was to provide a worthy perceived experience that was incorporated from the beginning of the project, at the center of the users' needs and perspectives. In this way, visually impaired people are able to use the final product with a great deal of success and "feel the view" and the "time" in a variety of cases. Although the initial target was a great and difficult challenge from the design point of view, the designed product and its results from the evaluation phase, proved encouraging for the future of designing for visually impaired users.

The results of the evaluation revealed that the system is rated as 'Medium Good'. This means that the system is quite usable and could be used to assist the visually impaired in absorbing valuable information regarding the real time progress of a live soccer event using a selves-developed tactile interface.

However, the evaluation also revealed the aspects that could be improved. These aspects involved the user experience while using the system. More specifically, the criteria of User Experience (UX) are considered as the most important as UX has the highest weight. In the particular example, the first three criteria of User experience had lower values than the others criteria. Those values affected a lot the final values of the evaluation since the weight of UX was high. Therefore, it is among our future plans to improve the invasiveness, the natural expression of action and the cognitive load required to use the system.

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