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The Use of Biofeedback For a Human-Centred Approach to Improving Cardiovascular Magnetic Resonance Imaging

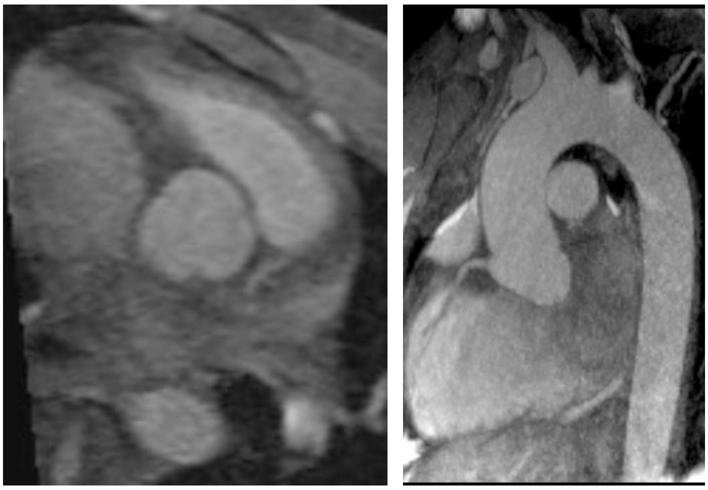
The goal of this research project was to develop a human-centred approach to improving Cardiovascular Magnetic Resonance Imaging (cMRI) in terms of: faster scan times for improved patient comfort and throughput; better image quality for more accurate diagnosis; greater understanding of patient state for enhanced patient-operator interactions.

Summary of Research Work Conducted

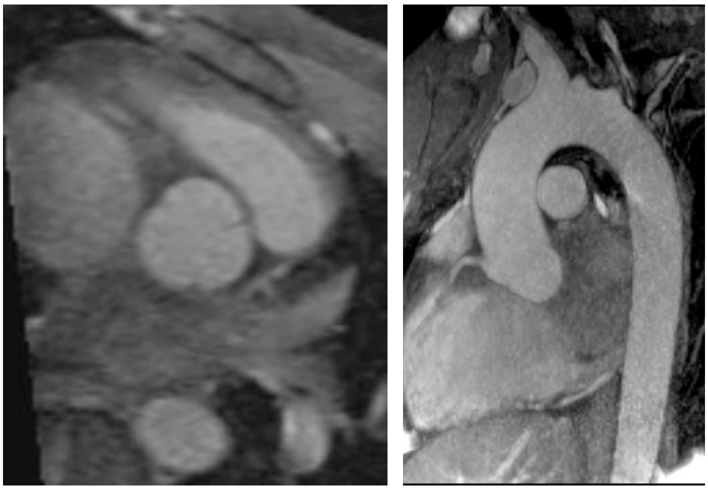
(A) MRI Scanner Technique Development (Permi Jhooti)

The necessary techniques, within the MRI hospital environment, to enable full utilisation of the biofeedback techniques were implemented. The CLAWS technique (1,2) was finalised to provide an automated system to enable efficient acquisition of data and provide images to be acquired at all breathing states, as opposed to the previous techniques, which only allow one image to be acquired at one breathing state. This provides the foundation for all the biofeedback work. To enable fully patient-friendly techniques, they must be fully adaptable to each individual patient during the scan. For this to be possible, the underlying MRI techniques must be capable of coping with the differences between patients and within patients during the course of a scan. The final implementation of CLAWS enables such flexibility in the biofeedback work providing focus to shift on the development of more complex and engaging experiences for the patient.

(a) CLAWS without rBF (Respiratory efficiency = 50%)



(b) CLAWS with rBF (Respiratory efficiency = 74%)



The image above demonstrates the increase in respiratory efficiency with the use of biofeedback

(B) Biofeedback Design (Jan Torpus, Permi Jhooti, Samuel Hanselmann, Andreas Simon)

The first study looked at visualisation of breathing in a game-like scenario where subjects are guided to breath with a more stable end-expiratory position. The results demonstrated that images acquired with visual biofeedback provided the same image quality with a significantly reduced scan time due to the more stable breathing pattern which resulted (3,4,5). However, this study was limited in that only one biofeedback module was available for the patient with a simple and direct visualisation of the breathing. A visual breathing task for one patient may not be so effective or appropriate for another and work was therefore focussed on an analysis of different visual representations of breathing.

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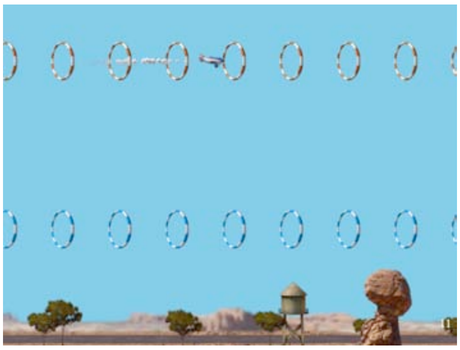
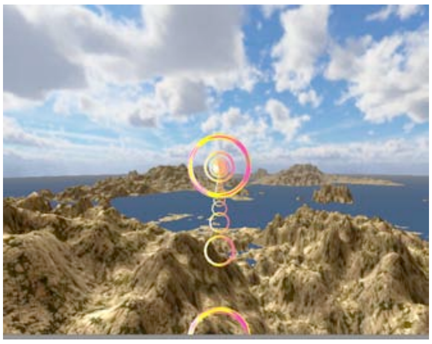
(i) Analysis of the existing interaction approach

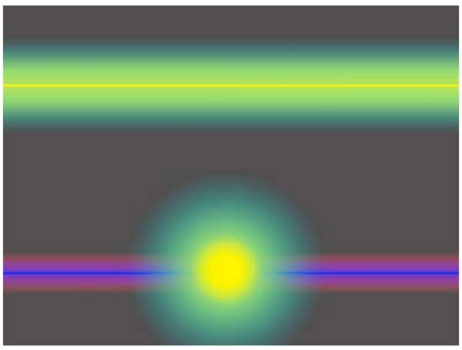
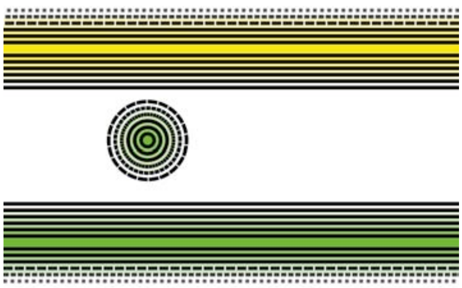
Approach: We analysed the original "aeroplane interface". The users are invited to interact by breathing in and out and thereby moving an aeroplane up and down. The mission is to fly through target rings at the EE and EI levels. We transferred the interaction mechanism and the mission from the 2D interface to a 3D interface to explore the impact of immersion.
Insight: Transferring the 2D interface to a 3D interface created a more impressive game-like impact of immersion. The problem was that the users would identify and interact more physically with the interface and therefore move around more, which would decrease the image quality.

1a. 2D aeroplane interface
1b. 3D aeroplane interface

(ii) Visual adaptations of existing interaction approach with soft target areas

Approach: One of the inconveniences spotted of the "aeroplane interface" was that users tried to avoid hitting the target rings since they looked realistic and might have caused damage to the aeroplane. We therefore started to develop approaches with the same interaction mechanism of moving up and down but with abstract elements and soft target areas. We experimented with changing colours of the interactive body to guide it towards the same coloured target area.
Insight: We found out that the correlative proportions of the elements and the position of the elements on screen need to be further studied before defining final designs (see 6.). Since one scan can take up to 10 minutes too colourful, bright or visually irritating designs can be tiring after a short period of time. Colour codes were not understood easily.

2a. 3D interface with lit elements and changing colours for guidance
2b. Interface with moiré effects and changing colours for guidance

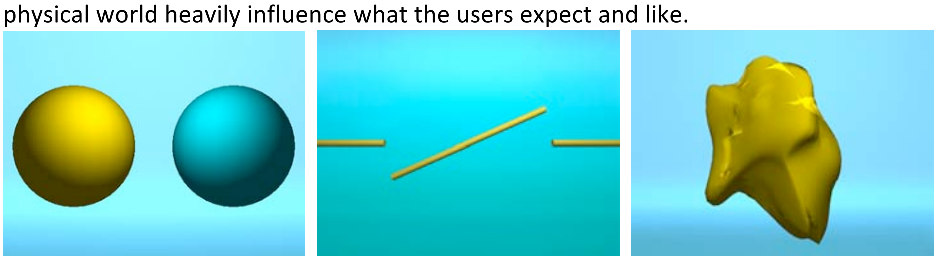
(iii) Exploration of various interaction and media approaches

Approach: As a next step we more freely experimented with alternative interaction mechanisms leaving the up and down approach beside. We tried out changes of visual parameters (change of colour, change of transparency, etc) and approaches of composition (morphing from one body to another, composing a scene, etc.). Apart from experiments with the interaction mechanism we tried out different types of media (3D, video, audio, still image).
Insight: Since one breathing cycle is approximately 4-7 seconds and the main focus was set on the visualisation of the mechanism of breath, many approaches had to be dismissed. Scenes and complex movements need to build-up too fast to develop a story and allow entertaining variance.

3a. Interface with changing still images which get composed by breathing in and out
3b. Interface with a painting which gets slowly composed by layers
3c. Interface with 3D bodies which get de/composed

(iv) Standardised geometric parameters

Approach: After expanding the possibilities of interaction mechanisms and media approaches we reduced the options and created a standardised set of basic interfaces. They were all made in 3D, simple comparable shapes (globe, cube, tube), two colours (yellow and blue) and simple interaction mechanisms and missions (colour > match colour, transparency > make invisible, position > hit target, size > cover area, rotation > get right angle, distortion > shape perfect body, etc.).
Insight: The approach helped to compare basic functions and missions of interfaces without comparable design and art features and to find out peoples preferences. Basic rules from our physical world heavily influence what the users expect and like.



4a. Basic interface with the mission to match the colour of the other globe
4b. Basic interface with the mission to turn the centre tube into perfect horizontal position
4c. Basic interface with the mission to create the perfectly shaped globe

(v) Backgrounds

Approach: After the decision to reduce the interaction to very simple objects and missions we wanted to experiment with the potential of entertaining backgrounds.
Insight: To optimally comply, the users should not get off the track by a too monotonous loop of interaction nor should they be distracted or stressed with too difficult missions. Relaxing motions in the background seem to detach the users from their surroundings and introduce them into the flow of interaction.

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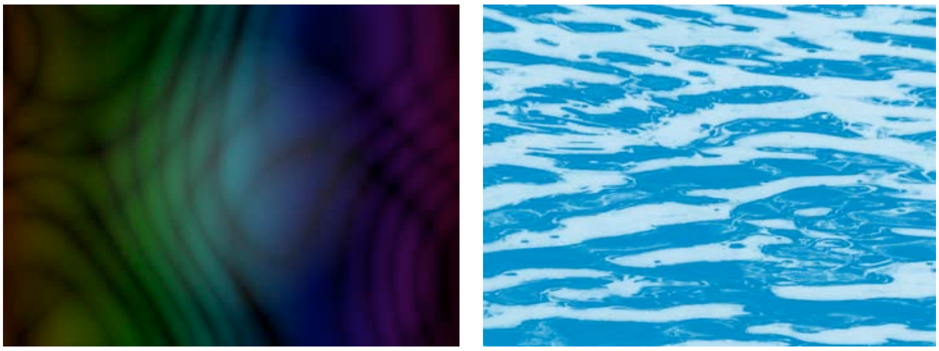
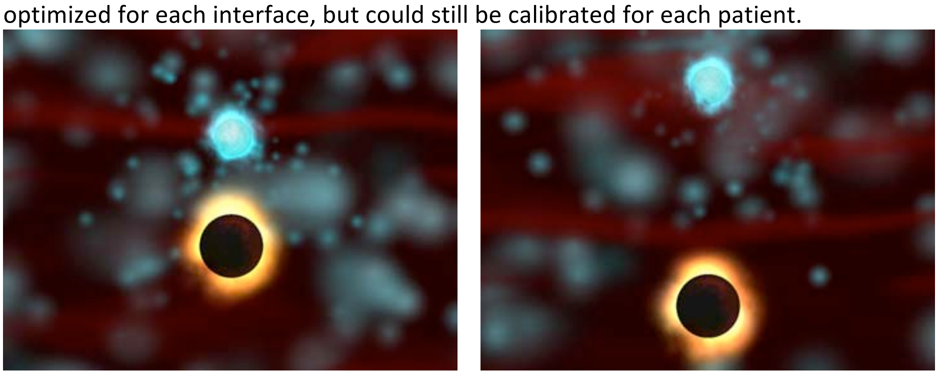


5a. Synthetic animated background with slow transitions
5b. Video background with visual effects

(vi) Interface layout and calibration

Approach: As mentioned under point (ii) the correlative proportions of the elements and the position of the elements on screen are crucial to the interface design and user interaction. Since the interfaces need to get calibrated for each patient before the interaction process the layout has to be adaptive. We first solved layout questions by changing audiovisual parameters: different positions and different scales for different personal breathing behaviours. This led to unfavourable proportions of interaction on the display, e.g. short distances for play on screen.
Insight: By calibrating the speed of the interactive element, rather than the position and geometric parameters of the targets and the mission, the interaction design could be stably optimized for each interface, but could still be calibrated for each patient.



6a. Cosmic interface with deteriorated proportions for play caused by layout calibration
6b. Cosmic interface with optimized proportions for play

(vii) Pacer

Approach: Up to now interaction concepts only focussed on gaining equal EE and EI levels but not on the regularity of breathing. Introducing a pacer allows temporal control and introduces the notion of rhythm. With a pacer not only the amplitude but as well the interval can be influenced. The patient can be guided along the dynamically adaptive personal rhythm.
Insight: We found out that people sometimes could not clearly make the difference between following the pacer or creating the feedback signal of their own respiration. This happened when the interface was perfectly calibrated to their personal breathing cycle. This led to a study of comparing the pacer with the biofeedback signal and to the new approach of programming an algorithm of a constantly calibrating pacer. This pacer is a mix between the two and represents the personal biofeedback but at the same time subtly guides the patient.

(viii) Auditory approach

Approach: Visual feedback was used to indicate diaphragm position. No other aids were given to help a patient regulate their breathing. Studies were therefore carried out to explore the effects of sound on the breathing rhythm. Sounds were used to simply guide the subject to breath in and

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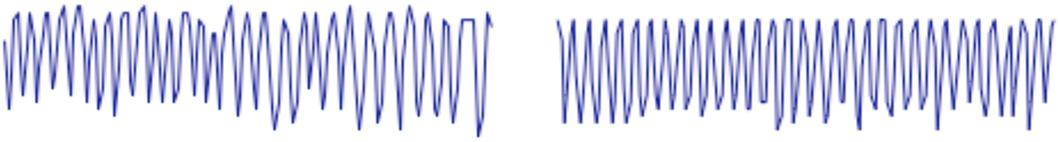
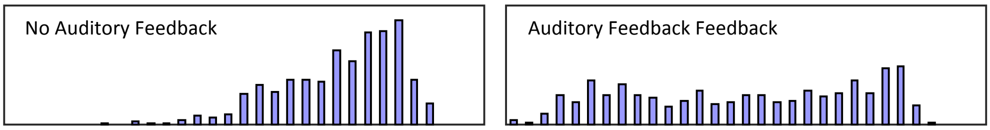
out at regular intervals to a variety of different timings, each timing designed to elicit a different type of breathing pattern: more stability at end-expiration, symmetrical breathing in and out, and more relaxed 'yoga' type breathing.

Insight: Auditory feedback has demonstrated a very good potential for regulating the diaphragm position based simply on timings and not position. By regulating the timing, the subject is consequently aided in naturally regulating their diaphragm position.

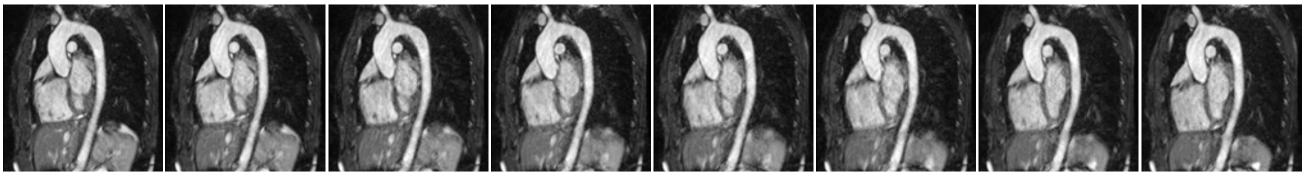


(a) Diaphragm Position (without rBF) (b) Diaphragm Position (with rBF)

(7) The image above shows an example of improvement in regularity of the diaphragm position with the use of auditory guidance.



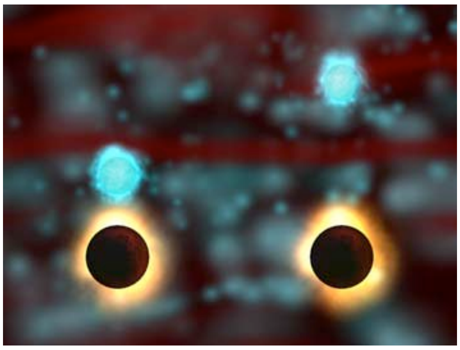
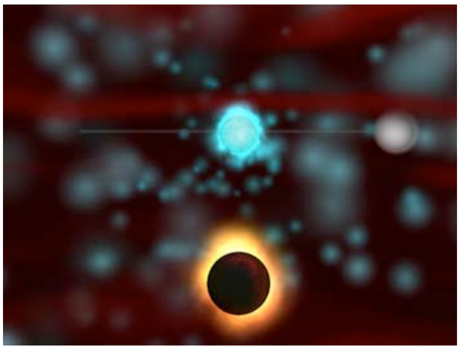
(8) The image above demonstrates the effect on the breathing profile when a rhythmic pattern to encourage a more even breathing-distribution is used. The corresponding images through the respiratory cycle are shown below.



(ix) Combination of pacer and biofeedback

Approach: Using a pacer exclusively results in monotony and creates a lack of motivation for compliance. Exclusive use of indication of the own biofeedback signal lacks of guidance. This situation leads to the approach of combing the two visual interfaces.

Insight: The combination of the two approaches resulted in an information overflow. Patients got confused and were not sure anymore which the interactive element was. The task to bring pacer and indicator into accordance was considered stressful. Even when we reduced the representation of the pacer to a background level and removed the target of the pacer, we observed that people would be stressed. Visually following a pacer and trying to hit a target at the same time is a redundant system anyway.

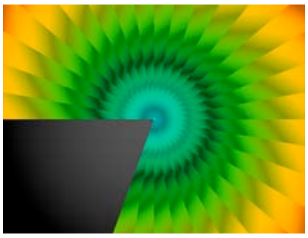
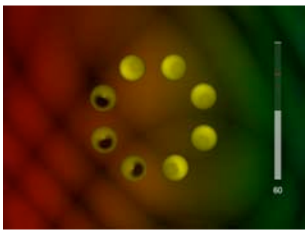
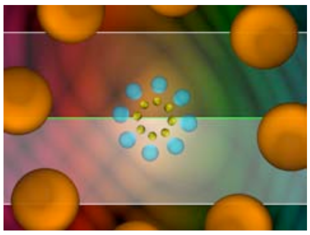
9a. Split interface with pacer and biofeedback signal at a glance
9b. Split interface with a visually reduced pacer and biofeedback signal at a glance

(x) Combining visual and auditory approaches

Approach: Dividing pacer and biofeedback representations on two different senses, is a promising user interface approach.
Insight: To reduce the confusion and stress complex visual user interfaces seem to generate, we started to split the representation of pacer and biofeedback on different senses: seeing and hearing. We explored the use of sonic and visual interfaces as separate channels to represent the patient’s biofeedback or the pacer at the same time. We compared the two possible combinations: sound for pacer / image for biofeedback and vice versa. The combination of visual pacer with sonic feedback seems to be most promising, since vision is perceived more as a dominant and exterior medium to guide and sound more as an internal “hidden” medium to represent personal feedback.

(xi) Timer

Approach: A standardised timer element can be introduced.
Insight: To reduce uncertainty about the temporal development during the scanning process we introduce a time information layer. It is especially useful for breath holding approaches during a scanning process.
First we experimented with recognizable watch-like timers. Later we introduced a standardised time slider, which can be added to each existing interface as an additional semi-transparent layer of information. The Slider can be used as a score system too.

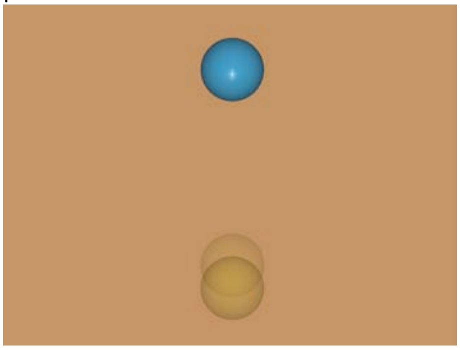




11a. Interface with a watch-like timer
11b. Interface with a timer as a neutral additional element
11c Interface with a timer as a neutral background element

(xii) Approach: History functions

Approach: Introduction of history functions can be represented as traces.
Insight: We explored the use of representations of passed EE and/or EI points. In a simple interface the interactive sphere leaves a trace each time it reaches the EE point. Each generated trace starts to slowly fade out and gets overlapped by the next one being left behind. This approach visualises the last 3-4 reached EE points. The more recent ones are more opaque than the older ones. It is helpful for the users to be able to compare former results with the current

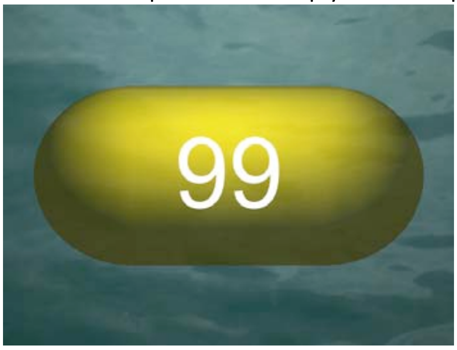
one and to be get aware of tendencies. By overlapping the traces as well create an average position which over time coincides with the calibrated personal position for each user.



12. Interface with blue globe leaving traces at EE points which slowly fade out

(xiii) Additional game features

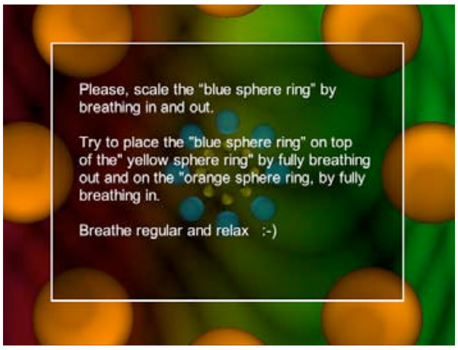
Approach: To further motivate the patient to comply, reward systems can be introduced.
Insight: The use of game-features in the hospital context needs to be studied according to target groups and the health situation of the patients. However, in appropriate cases the implementation of reward systems can encourage the patient to get more engaged with interaction. Audiovisual reward effects for successful interaction and a score system can further motivate the patient to comply and to improve the results.



13. Interface with visual reward and a number for the personal score

(xiv) Info panels

Approach: Information panels can be inserted for standardised instructions and feedback in the overall scanning process to improve and extend the communication between patient and operator.
Insight: The communication between operator and patient is organized with a two-way intercommunication system. The operator can always open the communication channel to ask the patient about her/his affective state or to give explanations and instructions. The patient can activate a physical device and thereby open the communication channel when there is a problem. The psychological hurdle to press the button and to possibly interrupt the scanning process is quite high and the patient is left alone during the normal scanning process. Introducing pre-processed audio or written information can improve the feeling of being accompanied and of being on track. Continuous explanations of the process, instructions of interaction tasks and feedbacks of the current state during the process can considerably improve the overall scan experience for the patient.



14. Interface with information panel giving instructions or feedback to the patient

The Toolbox – final design approaches

As a final result of the design developments we composed a collection of interfaces which can be chosen by the patients for certain studies. They are structured as a toolbox of audiovisual components which can be used in very basic modes or can be combined and extended with additional features like timer, info panels, etc.

(C) Full Patient Experience

The initial project was to affect the breathing profile to improve high-resolution 3D cardiac images. However, the aims of this work are to use human-centred approaches to improve MRI. The MRI experience of a patient, however, are not limited to the time spent within the scanner.

(i) Appointment	(ii) Hospital	(iii) Scan		(iv) Visualisation

The Patient Experience starts the moment the patient is invited for an MRI scan.

The cardiac MRI scans that were initially tested with biofeedback are often performed at the end of the MRI exam (shaded section above), when the patient has been in the scanner for over 30 minutes. Whilst the biofeedback techniques were very promising, many problems were highlighted during the studies as to the drawbacks of using such techniques in routine scanning. Stress and anxiety is a common cause of irregular breathing and motion during the scan. Whilst the use of biofeedback can aid this, to be fully effective the concerns of the patient need to be addressed at an earlier stage to ensure the patient is still happily in the scanner at the important end stages of the examination. There is no guarantee they will be happy to get into the scanner or even turn up for the appointment!

(i) Appointment: Pre-Hospital Experience

The anxiety of a patient can start from the moment a MRI scan is scheduled and it is important to engage the patient from the initial stages to ensure the entire MRI process is minimally stressful. A study was carried out in conjunction with TU Delft to explore how children can be prepared for an MRI scan before they enter the hospital. This has led to valuable insights which have also impacted on the design of the MRI Scan Experience Visualisations to incorporate the sense of a journey for a child from the moment a scan is scheduled to the end of the scan which may be several weeks later.

The patient experience starts from the moment the MRI is scheduled. The information-guidance-relaxation process should start here.

(ii) Hospital: Pre-Scan Training

As the visualisation system will require the patient to undergo tasks and is an additional stimulus for the patient, it is important to prepare the patient appropriately. Allowing the patient to play with the system prior to entering the scan is important for full effectiveness of the biofeedback. A system is currently being developed for the Evalina Children's Hospital in London to test the use of a pre-play system in conjunction with an MRI system to affect Breathhold imaging.

(iii) Scan: MRI Scan Experience

Preliminary work is underway to explore the use of a full MRI exam biofeedback system. The patient will be guided throughout the scan with the visualisation system used for: guidance, training, information and relaxation. The aim is to relax the patient throughout the scan to ensure the optimal images can be acquired at the important end-stage of the examination. The first module is targeted towards children, a population who often suffer from the stress of an MRI examination. Initial biofeedback modules were targeted on tasks which would take no more than a few minutes. The requirement for a feedback system which may be used for an hour require an alternative approach to engage the patient for the duration of the scan. The use of video, audio environments and immersive 3D worlds are being explored (Niki Neecke, Tabea Rothfuchs, Marcus Braach, Yvonne Lugtenburg).

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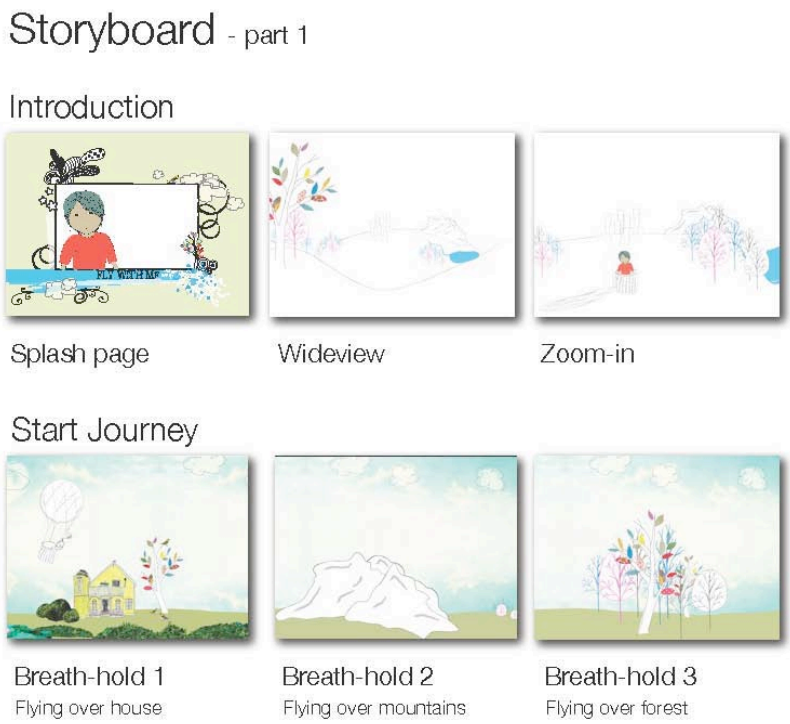

Figure: Storyboarding for children's full scanner experience biofeedback module.

(iv) Visualisation

The effectiveness of the biofeedback visualisations is affected by the quality of the visualisation possible within the scanner. The sense of an immersive relaxing environment was not possible with the current methods of visualisation within the scanner. A "perfect" 3D environment where the patient can be drawn away from the limited surroundings of the scanner would be the ideal setting as the projected scenery could suggest, for example, wide open spaces and eliminate any cause for claustrophobia. Furthermore, the artificial environment could be populated with visual clues that suggest an alternative interpretation of the scanner noises as well as provide interactive elements of a biofeedback program. Such a perfect environment will be out of reach of this first exploration but will serve as reference against which the validity of the first and intermediate steps will be measured. The first approach will be based on the construction of a curved "visor" which will serve as a projection screen. The projection will already be active while outside the scanner and will travel with the patient as he enters the scanner, thereby providing a gradual transition from the open space to the enclosed environment. The visor will be placed so that it will fill the largest possible part of the patient's field of vision. While we will seek to compensate for the loss of focus on the outer parts of the curved projection surface, we will also take advantage of this by giving the patient a natural "center of focus". We anticipate that a coordinated interplay of content and curved, variable-focus projection will be a substantial improvement over the current state of the art. This project has been

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carried out in collaboration with KnowRes (Basel) and TU Delft.

Figure: Design of an in-Scanner Visualisation System

(D) Operator Experience

Tools are also being developed to aid the operator for ease of use of the systems as well as improved communication with the patient, two factors which can again impact on the patient experience and the results of the MRI examination. An iPad interface is being developed to remove the technical aspects of the biofeedback system so the operator can more focus on the patient needs (Markus Braach).

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