Visuoperceptual profiling and game-based rehabilitation in children with cerebral visual impairment

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Abstract

Cerebral visual impairment (CVI) is a brain-based visual disorder. Children with CVI experience heterogeneous impairments both in their basic visual orienting behaviours and in their visual perception. For instance, children show eye movement difficulties, are unable to recognize objects, or cannot find their favourite toy in a cluttered toy box. CVI lowers quality of life and poses a great economic burden, but despite these concerns, no standard treatment for CVI exists. In this PhD, we developed a quantification schema of visual orienting functions and visual perception, enabling the development of an individualized and adaptive game-based rehabilitation programme for CVI.

PhD summary

The heterogeneity present in cerebral visual impairment (CVI) calls for 1) quantified profiling of a child's strengths and difficulties to better understand the child's needs, and 2) development of a rehabilitation strategy that can be individualized and adapted to each child's profile, as one therapy cannot fit all children.

To better understand the heterogeneity in CVI, in the first two studies, we developed a means to quantify children's profiles in daily life using a questionnaire and in the clinic using a visuoperceptual test battery. In the **first study**, using an exploratory factor analysis, we retrieved a five-factor biologically and clinically plausible model which explained 56% of the total variance in the responses on 485 parent-reported Flemish CVI questionnaires, indicating daily life CVI symptoms (1). The five factors retrieved were: 1) object and face processing impairments, 2) visual (dis)interest, 3) clutter and distance viewing impairments, 4) moving in space impairments, and 5) anxiety-related behaviours. We found that children with CVI scored significantly higher on factor 1 to factor 4 compared to children without CVI, hence this model differentiated between children with and without CVI. By scoring children's daily life visual functioning according to this factor structure, a clearer picture of the type and severity of impairments present is obtained, serving as a first step towards more targeted therapy.

In the **second study**, we developed a visuoperceptual profiling schema reflecting children's visuoperceptual strengths and difficulties (2). We conducted a Delphi study including individual interviews and two questionnaire rounds involving both researchers and clinicians, experts in the field of visual perception. The Delphi study provided an understanding of which visuoperceptual dimensions are targeted by which visuoperceptual subtests administered in the clinic during the CVI diagnostic procedure. Expert consensus resulted in six visuoperceptual dimensions, namely, 1) visual discrimination and matching, 2) object or picture recognition, 3) visual spatial perception, 4) figure-ground perception, 5) motion perception, and 6) visual short-term memory. We found that while all six dimensions differentiated children with CVI from those without CVI, the most discriminating dimensions were object/picture recognition ($r = 0.56$), visual spatial perception ($r = 0.52$), visual discrimination and matching ($r = 0.47$), and figure-ground perception ($r = 0.39$). Therefore, quantifying a profile according to these six visuoperceptual dimensions can be used to characterise/map dysfunction and intact functions in children with CVI, further highlighting the most important skills that need training (see Table 1).

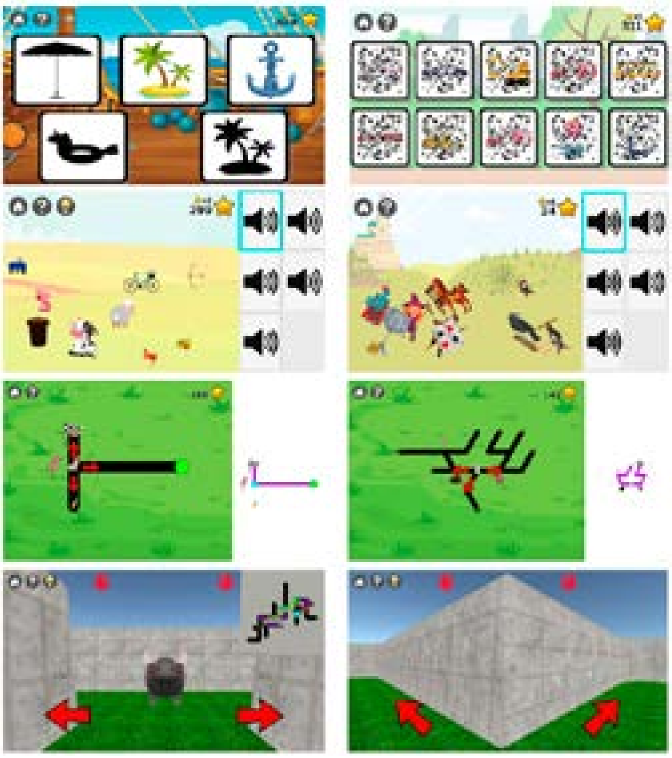
Results

In the **third study**, based on the visuoperceptual profiling schema, we developed individualized and adaptive mini-games (iVision mini-games) for children with CVI with a developmental age between 3-12 years (3). First, an informant-led design entailing focus groups with parents and therapists was used to elicit the user requirements and the gameplay of children with CVI, therapy goals, context of use, and the barriers and facilitators with which our rehabilitation would need to comply. Second, we proceeded to perform brainstorming sessions to generate game ideas within the development team, which resulted in the creation of four mini-games. The four mini-games named 1) MatchMaker, 2) Hurricane Chaos, 3) Maze Explorer 2D, and 4) Maze Explorer 3D can be seen in Figure 1. In MatchMaker, the goal is to find the most similar pair of cards, while prototypical images on the cards have undergone different manipulations, more specifically, details differ, different poses, missing parts, partial, atypical, silhouettes, contour, closure, noise, and viewpoints. MatchMaker aims to train mostly visual discrimination and matching, object/picture recognition, and figure-ground perception. In Hurricane Chaos, a hurricane has jumbled the objects and after clicking on the loudspeaker icon, a voice-over instructs which object the player has to find in the "chaos" in the jumbled scene. Hurricane Chaos aims to mostly train object/picture recognition and figure-ground perception, as well as visual discrimination and matching. In Maze Explorer 2D and Maze Explorer 3D, children have to navigate through and exit a

2D maze or 3D maze, respectively. The correct path and maze finish point are indicated in the mini map (another map on the right-hand side of the screen). These two games aim to target visual spatial perception, motion perception, and visual short-term memory. These mini-games integrate three key features, 1) Entry-level individualization: each child's average z-score on each of the six visuoperceptual dimensions is defined after the child undergoes visuoperceptual testing with an extensive test battery and 2) In-game adaptivity: the automatic adaptation of difficulty levels of the mini-games to the child's performance. These key features aim to place the child in the "flow" state in which a match between challenge and skill level is constantly attained. For instance, when the game is too easy, a more difficult level is shown next, whereas, when many errors are made and the child takes too much time, an easier level is provided. 3) Gameplay log-data: collected via an online dashboard that stores information such as the child's score, use of hints, time taken per game, errors etc. Third, in workshops, researchers and clinicians evaluated the rehabilitative game content by rating the manipulated images on their perceptual difficulty to create differing difficulty levels. Fourth, the researchers and clinicians linked the visuoperceptual dimensions to the mini-games and entry-level difficulty as well as defined adaptivity rules and evaluation criteria. Finally, we conducted formative testing including usability and player experience with researchers, clinicians, and neurotypical children. Researchers and clinicians rated the games highly, while neurotypical children highlighted several usability difficulties specifically in understanding the instructions, however, player experience was high. Feedback hereof was used to modify the games.

In the **fourth study**, we tested the feasibility of the newly developed visuoperceptual mini-games in 21 children with CVI. Children played the iVision mini-games in three sessions, in which their usability and player experience were registered using observations and questionnaires (Ben Itzhak N, Franki I, Laenen A, Wagemans J, Ortibus E. Usability and user experience of an individualized and adaptive game-based therapy for children with cerebral visual impairment. 2022, under review). While children reported a positive player experience, usability testing revealed problems in terms of effectiveness, understandability, and game design. Gameplay log-data revealed that in MatchMaker, children were challenged by the closure, missing parts, atypical, and noise manipulations. In Hurricane Chaos, children's visual search improved. Playing Maze Explorer 2D increased their navigational efficiency, while training with Maze Explorer 3D with both an egocentric (turning mini-map, self-centred) and allocentric (static mini-map, independent of view of child, based on environmental cues) representation was needed to improve navigation. Usability observations revealed the importance of integrating different elements into game design. Specifically, lessons learnt revolved around the following themes: tailored interactions/gestures/instructions, language, providing player control, familiarization time, balancing help and challenge, autonomy, avoiding fine motor skills and multiple sequences of actions, and integrating visual simplicity and consistency. Moreover, lessons learnt from player experience highlighted the necessity to integrate reward, challenge, immersive realistic experiences, immediate feedback on actions, and a rich media experience. This study resulted in further modifications of the games in terms of game content, visuals, and integration of stricter evaluation criteria. Therefore, a future Randomized Controlled Trial (RCT) should evaluate the effectiveness of training with these games on improving visuoperceptual functions and the transfer to tasks more similar to those encountered in daily life.

Figure 1: Example levels from the four iVision mini-games (3).
Notes. The left column shows examples of easier levels, while the right column shows examples of harder levels in the mini-games. The top row shows the MatchMaker game, the 2nd row the Hurricane Chaos game, the 3rd row the Maze Explorer 2D game, and the bottom row the Maze Explorer 3D game.



Finally, in the fifth study, since not only higher-level visuoperceptual skills but also basic visual orienting functions are impaired in CVI, we integrated a preferential looking eye tracking paradigm into the testing of children with CVI during their intake procedure (4). In this eye tracking paradigm, children were shown six different visual stimuli (e.g., simple cartoons) in one of four quadrants while their spontaneous eye movements were recorded. We aimed to quantify and relate a child's visual orienting functions to their daily life functioning and visuoperceptual abilities. Children who had impaired object and face processing impairments, greater visual (dis)interest, worse visual spatial perception and worse object and scene recognition had slower orienting responses to the visual stimuli. These novel results indicated that the integration of visual orienting function measurements with existing visuoperceptual assessments provide a better clinical picture. This study demonstrated the intricate relation between basic and higher-order stages of vision and the impact of visual orienting and visual perception difficulties on daily life functioning. In addition, it highlighted that, in clinic as well as in research, CVI should be approached from a holistic perspective.

To conclude, the development of serious games for children with CVI is a complex process, for which several steps following a multidisciplinary perspective are needed. Strengths and difficulties in everyday life and in standardized neuropsychological testing in children with CVI can now be quantified, providing ways to train skills in a personalized manner. In addition, visual orienting dysfunctions, easily detected by the preferential looking eye tracking paradigm we used, are potentially an early marker of higher visual perceptual deficits and add to the child's visual profiling. In the game development process, usability and player experience piloting phases provide invaluable information for optimizing games and should include researchers, clinicians, neurotypical children, as well as the target population.

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Table 1: Visuoperceptual subtests linked to the dimensions of the visuoperceptual profile (2).

Notes. Each child undergoes visuoperceptual testing and receives a z-score on each of the subtests and one average z-score on each visuoperceptual dimension. Beery-VMI-6: The Beery-Buktenica developmental test of visual-motor integration sixth edition; TVPS-3: Test of visual perceptual skills third edition; RAKIT-2: Revisie Amsterdamse Kinderintelligentie Test; PJLO: Preschool judgement of line orientation; NEPSY-II-NL: Developmental neuropsychological assessment second edition; OR: Object/picture recognition; VSP: Visual spatial perception; VDaM: Visual discrimination and matching; FGP: Figure-ground perception; MP: Motion perception; VSTM: Visual short-term memory. X's indicate the subtests that are used to quantify each dimension of the visuoperceptual profile.

TESTS	SUBTESTS	VISUOPERCEPTUAL DIMENSIONS					
		OR	VSP	VDaM	FGP	MP	VSTM
Beery-VMI-6	Visual perception		X	X			
	Visual-motor integration		X				
	Motor coordination		X				
TVPS-3	Visual discrimination		X	X			
	Visual spatial relationships		X	X			
	Visual memory		X	X			X
	Visual sequential memory		X	X			X
	Visual figure-ground		X	X	X		
	Visual closure		X	X			
	Form constancy		X	X	X		
L94	De Vos-task	X	X	X			
	Visual matching	X	X	X			X
	Line drawings occluded by noise	X			X		
	Overlapping line drawings	X		X	X		X
	Unconventional object views	X	X				
RAKIT-2	Figure recognition	X					
	Hidden figures	X	X	X	X		
PJLO		X	X	X			
NEPSY-II-NL	Geometric puzzles		X	X			
	Arrows		X				
Motion perception tasks	Motion-defined form	X			X	X	
	Global motion coherence					X	
	Motion speed					X	
	Biological motion	X				X	
	Average z-score	X	X	X	X	X	X