THE INFLUENCE OF VISUAL FIELD ON SOUND PERCEPTION IN CONCERT AUDITORIA

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1 INTRODUCTION

This paper represents the interdisciplinary work of UCL's Bartlett School of Architecture & Experimental Psychology and ARUP Acoustics. The work is situated at the nexus of architecture, acoustics and psychology.

The design of auditoria involves many disciplines which are to an extent siloed from each other. The required acoustic behavior informs the geometry and materiality of the architecture, and other factors such as the visual language of the space are left to the architect to develop in tandem with the taste of the client. Our research motivation with this work is to investigate how visual aspects of auditorium design might influence auditory perception and emotional response.

The findings of the work are significant for the development of new auditoria in terms of hall design and performance lighting. Our work here shows that there is still much to understand and much potential to refine in terms of a design process that fully embraces the cross-modal nature of human perception.

The paper introduces the background and theoretical framework of the study, before describing the methodology of a particular study, how it was designed, and the data collected. The results are tabled with findings and then discussed as to their interpretation and significance. The conclusion proposes broader implication for auditorium design, and logical next steps for study.

2 BACKGROUND & THEORETICAL FRAMEWORK

Significant research has been undertaken in cross-modal sensory correspondence; the impact of one sense in the perception of another. Foundational reviews on the subject have revealed that there are clear associations between subjective judgements of pitch and tonal brightness as well as loudness and lightness. (Spence C. (2011)[1] Classic studies showing that higher pitches are associated with brighter colours (Marks, L. E. (1987)[2] have a potential significance for architects or acousticians involved in acoustical design projects, as well as studies that have demonstrated direct matches between brightness of colours and the loudness of sounds. (Stevens, J. C., & Marks, L. E. (1965)[3].

Qualities of sound in music has been observed in terms of pitch, roughness, sharpness tempo and colour correspondences, (Sun, X., Li, X., Ji, L., et al. (2018)[4]. New studies on the relationships between pitch and colour have shown that higher frequencies mapped to yellow, even when colours we equillumient. (Hamilton–Fletcher, G., et al. (2017)[5]. In emotional terms, investigations between colour, hue / saturation, and musical pieces have shown a clear link between music, colour and emotional engagement. (Barbiere, J. M., Vidal, A., & Zellner, D. A. (2007)[6]. This is consistent with similar studies on emotional mapping music to colour patches achieving similar results. (Palmer, S. E., Schloss, K. B., Xu, Z., & Prado-León, L. R. (2013)[7].

Studies on the physiology of sound and colour correspondence have shown that pitch and brightness combined can influence reaction times of visual choices, (Bernstein, I. H., Eason, P. D., & Schurman, D. J. (1971)[8]

The links between cross-modal correspondences and synesthesia are well documented in selected cases, the work featured here is focusing on aspects of correspondences that affect a wider selection of the listening public, and aspects that are common to us all. We do share synesthetic perceptual qualities, (Ward, J., Huckstep, B., & Tsakanikos, E. (2006)[9] and the work documented here focuses on such aspects of perception.

However, despite the wide-ranging nature of research into colour and sound very little related research has been undertaken in the context of colour and auditoria acoustics. In a 2011 overview on the impact of colour on human behavior, no study on cultural buildings had taken place. (Jalil, N. A., Yunus, R. M. and Said, N. S. (2012)[10]. There is evidence of a study on colour preference and auditory phenomena undertaken in virtual environments, (Chen, Y. Cabrera, D. (2021)[11] and in 2022 a study was undertaken to look at colour and musical quality and emotion, (Hauck P, von Castell C, Hecht H, 2022) [12] but there have been no controlled studies undertaken looking at the role of visual stimuli on acoustic perception in a real space, with a real audience with live music, the understanding of which is critical to the real phenomena of communal engagement with live music.

3 METHOD

3.1 Research Design

This study employed a mixed-method experimental design to investigate how visual and acoustic variables influence perceptions of qualities of sound, as well as corresponding emotional responses, during a live musical performance. Participants were exposed to systematically varied room colour, performance lighting, and acoustic conditions while listening to the same piano piece performed live on stage. Both subjective and objective data were collected to capture perceptual and physiological responses.

3.2 Variables and Experimental Conditions

The experiment took place at Milton Court, a 600-seat concert hall within the Guildhall School of Music at the Barbican, London, on 7 October 2024. The hall features variable acoustic elements in the form of motorized overhead reflectors and fabric banner system. The auditorium's interior is characterised by timber diffusion at stalls and platform level and diffusing white plaster at balcony level. For the purposes of the experiment, the performance lighting system was altered to allow for the upper walls to be lit in different colours. Quiet incandescent lights with gel colour filters were used for this purpose, thereby enabling different wall colour conditions to be created.

Volunteer participants were recruited to listen to the same piece of music performed several times by the same pianist, with either lighting or acoustic settings (or both) changed in-between each performance. Participants were seated together centrally in two rows of the stalls, so that the conditions experienced by each participant were as similar as possible. The experiment was conducted in two sessions (Session A and Session B) each lasting approximately 60 to 75 minutes, and with a separate group of participants in each group. Session A comprised five performance presentations, while Session B comprised six. The condition variables were as follows.

1. **Room Colour:** Programmable wall lighting created five chromatic conditions: white, blue, green, yellow, and red to explore the impact of colour on perceptual and emotional responses (see photos in Fig. 1).
2. **Performance Lighting:** Lighting was varied between two modes: general overhead lighting and theatrical, platform-focused lighting. For the latter, no colour effects were employed.
3. **Acoustic Settings:** Reverberance was moderately varied using the auditorium's variable acoustic system. This was done using fabric banners deployed towards the rear of the room, out of the visual field of the subjects, so that there was no associated visual cue.

The music was an incomplete piano sonata by Schubert in F-sharp minor, D 571 that lasted for approximately 120s. This standardised musical performance was delivered by the same professional pianist on the same piano across all conditions to minimize musical variation. See Fig. 2. for the detailed setup of each presentation.

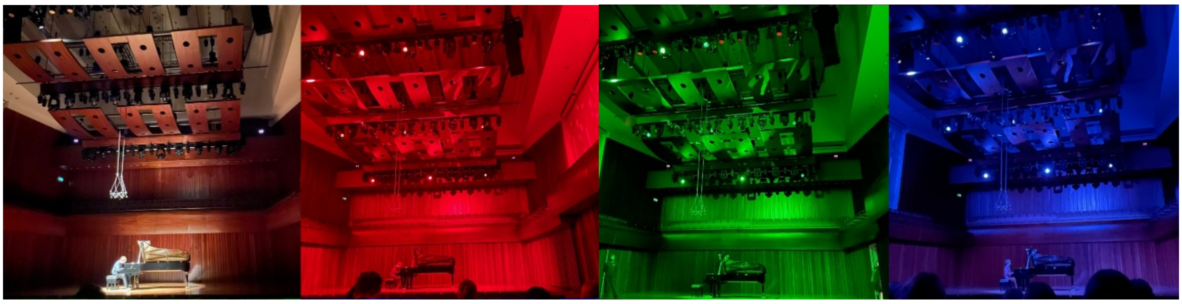

Fig. 1: Photographs of Varied Testing Conditions (Colours in Order: White, Red, Green, Blue)

Group A

Order	Acoustic Condition	Lighting Condition	Condition Label
1	1	Blue	1
2	2	White, overhead	2
3	2	White, theatrical	3
4	1	Green	4
5	1	White, overhead	5

Group B

Order	Acoustic Condition	Lighting Condition	Condition Label
1	1	Red	6
2	2	White, overhead	2
3	2	White, theatrical	3
4	1	Green	4
5	1	Yellow	7
6	1	White, overhead	5

Fig. 2a: Presented Setup (Acoustic and Lighting)

Acoustic Condition	EDT,s	T(20),s	T(30),s
1	1.5	1.7	1.7
2	1.4	1.6	1.6

Fig. 2b: Acoustic Conditions (High-Level Measures of Reverberation in the Unoccupied Room)

3.3 Participants

Participants were recruited through university mailing lists and public advertisements using voluntary sampling. All participants are over 18 years of age, able to see and hear. To be a fair representation of a typical audience, there were no exclusion criteria. All participants provided written informed consent; ethical approval was granted by the UCL Research Ethics Committee. Participants were informed of their right to withdraw at any time without providing a reason. Each participant was assigned a unique identifier at enrolment, and all data were anonymised to protect confidentiality.

Demographic and background information collected included age, gender, occupational status, educational attainment, ethnicity, and current mood (assessed on a 6-point Likert scale: 0 = “At no time” to 5 = “All of the time”). In total, 33 participants (F = 61%, M = 36%, X = 3%) participated in the study (mean age = 27.34, SD = 15.60). Music background varied: 52% (n = 17) reported personal interest, 42% (n = 14) professional involvement, and 6% (n = 2) specialist academic/research engagement.

Gender	F	20 (61%)
	M	12 (36%)
	X	1 (3%)
Occupational Status	Student	30 (91%)
	Occupied	1 (3%)
	Unoccupied	1 (3%)
	Retired	1 (3%)
Education	High School Graduate	8 (24%)
	Some College	6 (18%)
	College Graduate	9 (27%)
	Some Postgraduate Work	3 (9%)
	Postgraduate Degree	7 (21%)

Music Background	Professional	14 (42%)
	Specialist Academic / Researcher	2 (6%)
	Personal Interest	17 (52%)
Ethnicity	Asian / Pacific Islander	14 (42%)
	Hispanic or Latino	1 (3%)
	Native American or American Indian	1 (3%)
	Other	4 (12%)
	White	13 (39%)

Fig. 3: Participant Demographics, Total Participants = 33 (100%)

3.4 Data Collection

Participants were instructed to rate qualities of sound, and emotional engagement. After each listening condition, participants completed a structured questionnaire addressed to perceptions of nine sound qualities: clarity, reverberance, intimacy, loudness, envelopment, warmth, brilliance, tonal quality, and emotional engagement. Responses were recorded on a 10-point Likert scale (1 = "not at all” to 10 = "extremely"). These descriptors were selected based on established frameworks in psychoacoustics and auditorium design.

4 RESULTS & FINDINGS

4.1 Analysis Methods

Two principal modes of analysis were performed to examine the effect of conditions (lighting and acoustic) on subjective ratings of sound qualities. The first employed general linear models with covariate controls (GLM) to examine differences in mean ratings within each group between conditions; and with both groups pooled. The second examined differences in mean ratings in a sequence of paired comparison, i.e. it examined the overall significance of the changes in individual subject ratings of sound qualities as each condition changed. Although effectively limited to comparisons between successive conditions, this second analysis is less affected by inter-subject variability, and less vulnerable to aural memory diminishing over the course of the presentations as it represents a series of A/B comparisons.

4.1.1 Condition Variables

First, to allow for higher-level and modal effects to be investigated, beyond differences between colours, condition variables for the lighting were set as follows:

WhiteColour (Coloured=1, White=2)
Colour (Blue=1, White=2, Green=3, Red=4, Yellow=5)
OverTheatre (Wall Coloured=1*, Overhead White=2, Theatrical White=3)
*The wall mode was used only for the coloured condition

4.2 Mean Values of Subjective Sound Quality

Condition	Clarity	Reverberance	Intimacy	Loudness	Envelopment	Warmth	Brilliance	TonalQuality
1.00	6.35	6.18	6.00	5.29	5.71	5.94	4.76	6.29
2.00	7.16	6.33	5.61	4.79	4.85	5.76	6.79	6.70
3.00	7.78	6.47	7.00	4.50	5.50	6.47	6.91	7.34
4.00	7.00	6.27	5.17	4.70	4.85	4.76	5.85	6.15
5.00	6.73	7.06	6.45	4.79	5.82	6.58	6.73	6.94
6.00	6.07	7.36	5.71	4.93	5.69	7.50	5.36	7.14
7.00	6.87	6.47	6.21	6.00	5.00	6.13	7.21	7.07
Total	6.97	6.56	6.03	4.88	5.31	6.04	6.35	6.79

Fig 4. Mean values of subjective sound quality ratings by condition.

4.3 Differences in Mean Ratings

A GLM for Groups A and B pooled with WhiteColour, Acoustic Setting, Colour and OverTheatre as variables show overall significant differences for Clarity (p=,02), Intimacy (p=.007), Brilliance (p<.001); and marginal differences for Warmth (p=.082) and TonalQuality (p=,074).

4.3.1 White versus Coloured light

	WhiteColour	N	Mean
Clarity	1	79	6.67
	2	97	7.22
Reverberance	1	79	6.48
	2	98	6.62
Intimacy	1	78	5.63
	2	97	6.34
Loudness	1	79	5.11
	2	98	4.69
Envelopment	1	77	5.21
	2	98	5.39
Warmth	1	79	5.76
	2	98	6.27
Brilliance	1	78	5.77
	2	98	6.81
TonalQuality	1	79	6.53
	2	98	6.99

Fig 5. The table below shows means by WhiteColour

A simple T-test of differences in means by WhiteColour showed significant differences for Clarity (p=.028); Warmth (p=.013); Tonal Quality (p=.01); and a marginal difference for Brilliance (p=.052).

A GLM shows a significant difference for Brilliance (p=.028).

4.3.2 Acoustic Setting

	AcousticSetting	Mean
Clarity	1.00	6.69
	2.00	7.47
Reverberance	1.00	6.65
	2.00	6.40
Intimacy	1.00	5.88
	2.00	6.28
Loudness	1.00	5.02
	2.00	4.65
Envelopment	1.00	5.39
	2.00	5.17
Warmth	1.00	6.00
	2.00	6.11
Brilliance	1.00	6.05
	2.00	6.85
TonalQuality	1.00	6.65
	2.00	7.02

Fig 6. Means by AcousticSetting

A simple T-test of differences in means by AcousticSetting showed significant differences for Clarity (p=.002), Brilliance (p=.004); and marginal differences for Intimacy (p=.099), Loudness (p=.059).

A GLM shows a marginal difference for Intimacy (p=.066), Envelopment (p=.085) and Warmth (p=.091).

4.3.3 Overhead or Theatrical lighting

	OverTheatre	Mean
Clarity	1	6.67
	2	6.94
Reverberance	1	6.48
	2	6.70
Intimacy	1	5.63
	2	6.03
Loudness	1	5.11
	2	4.79
Envelopment	1	5.21
	2	5.33
Warmth	1	5.76
	2	6.17
Brilliance	1	5.77
	2	6.76

TonalQuality	1	6.53
	2	6.82

Fig 7. Means by OverTheatre.

A simple T-test of differences in means by OverTheatre showed significant difference in Clarity (p=.041) and Warmth (p=.004); and marginal differences in Intimacy (p=.077), Brilliance (p=.072) and TonalQuality (p=.066).

A GLM shows a significant difference for Intimacy (p=.004).

4.3.4 Colour

	Colour	Mean
Clarity	Blue	6.35
	White	7.22
	Green	7.00
	Red	6.07
	Yellow	6.87
Reverberance	Blue	6.18
	White	6.62
	Green	6.27
	Red	7.36
	Yellow	6.47
Intimacy	Blue	6.00
	White	6.34
	Green	5.17
	Red	5.71
	Yellow	6.21
Loudness	Blue	5.29
	White	4.69
	Green	4.70
	Red	4.93
	Yellow	6.00
Envelopment	Blue	5.71
	White	5.39
	Green	4.85
	Red	5.69
	Yellow	5.00
Warmth	Blue	5.94

	White	6.27
	Green	4.76
	Red	7.50
	Yellow	6.13
Brilliance	Blue	4.76
	White	6.81
	Green	5.85
	Red	5.36
	Yellow	7.21
TonalQuality	Blue	6.29
	White	6.99
	Green	6.15
	Red	7.14
	Yellow	7.07

Fig 8. Means by Colour.

A GLM shows a significant difference for Brilliance (p=.004).

The table below summarizes the results of a series of independent sample T-tests run between each Colour. The table indicates which sound quality ratings were significantly different between each colour. Parantheses are used where a marginal difference was observed.

The following abbreviations are used.

C	Clarity	L	Loudness	B	Brilliance
R	Reverberance	E	Envelopment	T	Tonal quality
I	Intimacy	W	Warmth		

	Blue	White	Green	Red
Blue				
White	C,B,(T), (L)			
Green	W, B,	I,W,B,T		
Red	R, W, (T)	C,(R),W,B	C,R,W,(T)	
Yellow	B, (T)	L	(I),L,W,B,(T)	(R),L,W,B

Fig 9. Independent Sample T-Test Results

4.3.5 Sequential Analysis

Sequential paired comparison results are shown in the tables below for each group separately. A "+" sign indicates a significant increase (p<.05) in value occurs when the condition changes, a "-" sign indicated a significant decrease, and the corresponding signs in brackets indicates marginally significant changes (p<.1).

In addition to the abbreviations employed above for the Colour analysis, the following are used.

Con	Condition Label	Col	Colour
AcS	Acoustic condition	M	Lighting mode

4.3.5.1 GROUP A

Con	AcS	Col	M	C	R	I	L	E	W	B	T
1 to 2	1 to 2	Blue to white	Wall to over	(+)			(-)			+	
2 to 3	2 to 2	White to white	Over to theatre			+					
3 to 4	2 to 1	White to green	Theatre to wall			-			-	(-)	-
4 to 5	1 to 1	Green to White	Wall to over			+			+	(+)	(+)

4.3.5.2 GROUP B

Con	AcS	Col	M	C	R	I	L	E	W	B	T
6 to 2	1 to 2	Red to white	Wall to over	+					-		
2 to 3	2 to 2	White to white	Over to theatre	+		+				+	
3 to 4	2 to 1	White to green	Theatre to wall	-		-			-	(-)	(-)
4 to 7	1 to 1	Green to Yellow	Wall to wall				+		(+)	(+)	
7 to 5	1 to 1	Yellow to white	Wall to over		+		-	(+)		-	

Fig 10. Sequential Analysis Results

4.4 Relationships between qualities of sound

Partial correlation analyses were run between each of the rated dimensions, with control variables employed (AcousticSetting, Colour, WhiteColour and OverTheatre). The summary below indicates which significant co-relations between rated dimensions were observed. These are all statistically significant positive correlations, with the exception of the significant negative correlation between Loudness and Clarity.

Clarity correlated with:	Intimacy, Loudness(neg) Brilliance, Tonal Quality.
Reverberance correlated with:	Envelopment, Warmth, Tonal Quality
Inimacy correlated with:	Clarity, Envelopment, Warmth, Brilliance, Tonal Quality
Loudness correlated with	Clarity (negative)
Envelopment with:	Reverberance, Intimacy, Warmth, Tonal Quality
Warmth with:	Reverberance, Intimacy, Envelopment, Tonal Quality
Brilliance with:	Clarity, Intimacy, Tonal Quality
Tonal quality with:	Clarity, Reverberance, Intimacy, Envelopment, Warmth, Brilliance

4.5 Summary

The group mean analysis suggests that condition variables have the following associations:

- Coloured light on average is considered more brilliant, but White is exceeded by Yellow
- Acoustic setting 2 (lower RT) was considered more intimate and warmer, but with less envelopment. This is the only situation in which envelopment changes.
- With theatrical light we see higher judgements of intimacy than with overhead light.

- Different colours are associated with significant differences in Clarity, Brilliance, Warmth and Tonal Quality. Green and Blue are associated with lower Warmth than are Red and Yellow. Red is associated with the highest Reverberance and Tonal Quality. Green is generally associated with the lowest Intimacy, Envelopment, Warmth and Tonal Quality. Yellow is associated with the highest Loudness and Clarity ratings.

The sequential analysis reinforces some of these observations, certainly the greater Intimacy associated with theatrical lighting, and significant changes in Warmth, Brilliance and Tonal Quality. Differences in Envelopment, Loudness and Reverberance are less clear.

5 DISCUSSION

The experiment was conducted in a window of opportunity occasioned by other music-acoustical exercises being conducted at Milton Court on the same day. As such, there were practical constraints, and it was not possible to implement a fully balanced (eg. Latin Square) design. Therefore, there is a likelihood of order effects being present, and associated challenges in independent analysis of factors, although the sequential analysis does represent a series of true A-B comparisons. Equally, there are likely to be cultural differences in the understanding and use of the rating scales within the relatively small participant groups.

Nevertheless, the results do suggest evidence towards interesting associations between subjective qualities of sound and lighting as well as acoustical conditions. The coloured lights were used to simulate differences in room colour (i.e. interior design choices), and the results certainly suggest that aspects of perceived sound quality are significantly influenced by room colour and performance lighting mode.

While different colours were linked to variations in qualities of sound that have visual associations—such as Brilliance and Warmth—there were also notable differences in judgments of Loudness and Tonal Quality. The explicitly spatial aspect of sound (Envelopment) generally was less influenced by visual factors.

The test results generally agree with those of Chen, Y. Cabrera, D. (2021), who found that colour influenced visual and auditory preferences. However, they differ in that they did not establish a link between colour and loudness or reverberation, whereas our tests did. Specifically, yellow was the strongest in affecting the sense of loudness, and red significantly influenced the perception of reverberation. It may be that the differences between virtual presentation with VR goggles in isolation and live presentation with other participants in a real auditorium may have a bearing on these results.

The ‘white’ light used in the tests was 3700k, which can be considered ‘warm’. The results showed a clear tracking between responses to yellow and white, showing that colour temperature also has an impact on perception. Saturation of light also has a role to play our perception of colour, and accordingly, cross modal correspondences. Aspects of psychology that may have a bearing on our results is the Helmholtz–Kohlrausch effect; the perceptual phenomenon where an intense saturation of spectral hue is perceived as part of a colours luminance, and ‘brightness’ can increase with saturation. Our studies show a possible link with acoustic brightness with chromatic brightness. Studies on such perceptual phenomenon need to also consider the effect of the Kruithof curve where a regions of illuminance levels and colour temperatures can be seen as either comfortable or pleasing, and areas outside can be seen as uncomfortable and unnatural. This has been observed in the tests that the impact of blues which was observed to affect clarity and yellows which was shown to affect loudness, brilliance and tonal quality should be considered when developing performances.

However, colour has strong cultural and symbolic meaning that varies across cultures, red can mean warmth as well as danger or good luck. The symbolic layering of colour can skew results, so an understanding of differing demographics and cultural bias towards differing colours is required to fully understand the impact of the studies.

We observed a bias of results towards natural conclusions; presentations undertaken with a yellow or red light implying 'warmth' in a performance, shows that there is more at play than a basic response to acoustics, and that memory may be playing a role in the perceptual experience. Other research has shown that language has been seen to be a driver in other forms of sensory congruence (Hamilton-Fletcher, et al. (2016)[13] 'low' frequencies implying 'deeper' and 'darker' colours, and the results here have shown that there is a correspondence with the visual and the acoustic. The findings in this paper also align with anecdotal evidence that audiences have felt that light and blue colours have rendered the musical experience 'cool' and darker wood toned rooms being warm. (Hyde J. 2004)[14]

Regarding further work that should be undertaken in the context of the findings of the tests, only primary colours, Yellow, Red, Green and blue were used in the tests. Further work is to be undertaken looking at colour blends, such as purple (red+ blue), orange (red + yellow) etc. to see what effect, if any this may have in acoustic perception. Could blends of colours generate blends of effects? Is there a relationship between complementary colours and complementary affects?

Whilst the results reported here are clear, it should be noted that cross modal correspondences are subject to context which can vary significantly (Spence, C., & Di Stefano, N. (2022)[15]. What is reported now, doesn't mean that the results would be the same in other contexts. Further study is required to look at other halls and situations and see what is repeatable; such as the tests were undertaken with a Schubert piano piece that had a limited tonal and dynamic range. Observing the impact of colour on perception through full orchestral works with greater dynamic range may draw out stronger reactions and more insights.

The results shown in this paper show that visual stimuli can influence acoustic perception, in the world of experimental psychology, 'why' this is happening is a wider question and can be answered with further research and investigation.

6 CONCLUSION

Corespondences between visual stimuli and acoustic perception were observed in the tests, with colour having an effect on perceived acoustic qualities of brilliance, warmth and reverberation.

The impact of colour on acoustic perception will have implications for architectural and acoustic design; Colour and sound corespondences can be used to align lighting and material colour schemes with acoustic content, creating a unified sensory atmosphere, heightening the emotional / immersive experience for audiences. Outside of auditoria, colour can reinforce acoustic zones, supporting wayfinding and cognitive mapping, thus quiet areas can be rendered in cooler tones, and active areas in warmer colours, helping users visually predict acoustic conditions.

The field of sensory congruence and architectural acoustics is crucial for becoming better designers who appeal to a broader audience. However, more research is needed to go beyond overall performance and examine the temporal aspects, exploring how frequency and colour influence each other over time.. This will reveal greater insights into the role of memory, the senses and experience.

Acknowledgements: *Thanks to Grace Lampkin, Ian Knowles, Sam Porter Frakes, Matthew Lomax of ARUP, James Alexander of Milton Court, Fiona Zisch and Hugo Spiers at UCL for support and advice.*

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