Migrating Deafspace Principles to the Dynamic Lighting of Lunar Surface Habitats

A Transferable Inclusive-Design Framework for High-Constraint Environments

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A lunar habitat has no natural day and night

29.5

Earth days

One lunar day-night cycle, against 24 hours on Earth

0.16 g

Partial gravity

Vestibular and proprioceptive input is altered

Months

Sealed and isolated

A small pressurised volume with severe resource limits

South pole

Low sun, deep shadow

Lit ridges beside permanently shadowed crater floors

THE SAME 29.5 EARTH DAYS



Earth gives the body 29 sunrises in this period. The Moon gives one. At the south pole, terrain and a low sun replace any regular daily rhythm.

Light must do three jobs at the same time

JOB 1

Set the body clock

In a cabin without natural daylight, light is the principal external time cue.

Flight data show sleep deficiency, circadian misalignment and frequent hypnotic use.

JOB 2

See and communicate

Glare-free visibility for visual communication and task work.

Light carries the information that communication depends on.

JOB 3

Orient and move safely

Unbroken visual information for wayfinding and emergency response.

At 0.16 g, visual cues are expected to carry more weight.

Existing designs struggle to deliver all three within a single system.

Sources: Barger et al. 2014; Flynn-Evans et al. 2016; NASA-STD-3001 Vol. 2 Rev. E

Cabin lighting moved from static lamps to dynamic LEDs

STATIC FLUORESCENT lighting as a visual-task utility

DYNAMIC LED lighting as a circadian countermeasure

1973–74
Skylab

Fluorescent luminaires at the start of long-duration habitation

1998–2016
ISS General Luminaire Assembly

77 fluorescent units, static light for visual work

2016
ISS Solid State Lighting Assembly

Three LED presets: 4500 K general, 6500 K alertness, 2700 K pre-sleep

2018
Orion cabin lighting

LED with circadian usage protocols

2021
Chinese Space Station

Cabin brightness and colour manually adjustable as required

Analogue and empirical studies, 2015–2024
HERA 45-day missions · Antarctic winter-over · isolation chambers

Standards, 2021–2023
NASA OCHMO technical briefs on Artemis lighting

Every stage answers the same question: when to deliver which light.

So far, “dynamic” has meant timing only

WHEN

Scheduling light over time

SSLA presets, Orion protocols and analogue experiments all answer this question.

✓ Addressed since 2016

WHERE and WHO

Spatial composition of light

Who is lit, from which directions, with what structure of brightness and background.

✗ Not yet in systematic design

HOW CONTINUOUS

Continuity of light information

Across movement, posture change and scene transition.

✗ Not yet in systematic design

?

RESEARCH QUESTION

How can one integrative framework guarantee that every crew member can see, communicate and move safely, with circadian and psychological regulation then added on top?

Relevant clauses remain dispersed across separate standards. Source for the research focus: Qu et al. 2026, scoping review of light and colour in space habitats.

DeafSpace treats light as a medium of communication

DeafSpace

Gallaudet University, from around 2005

- Space and proximity
- Sensory reach
- Mobility and proximity
- **Light and colour**
- Acoustics

Five principles drawn from the spatial experience of the Deaf community

The light and colour principle

WHAT INTERFERES WITH VISUAL COMMUNICATION

Glare
hides detail on faces and hands

Shadow patterns
fall across faces and hands

Backlighting
turns people into silhouettes

WHAT DEAFSPACE ASKS FOR

Soft | **Diffused** | **Adjustable**

It matches the two gaps, spatial composition and continuity.

Source: Bauman, DeafSpace Design Guidelines, Gallaudet University, 2010

Both settings place the same four demands on light

SOURCE DOMAIN · DeafSpace	DEMAND ON LIGHT	TARGET DOMAIN · Lunar surface habitat
Faces, hands and interlocutors are kept legible; sight lines are a design object	**Communication**	Briefing, coordination and medical work depend on the same legibility
Continuous optical cues carry orientation and safe movement	**Orientation and movement**	Partial gravity weakens vestibular cues, so orientation falls back on vision
Glare, backlighting and shadow are failures of communication, not of comfort	**Glare and contrast**	Low sun angle, deep shadow and bright surfaces make such failures more costly
Diffusion, adjustability and user control are requirements, not amenities	**Control and adjustability**	Light must be tuned across tasks, shifts and circadian phase in a sealed volume

In both settings light is the primary medium, not a background service. The analogy is drawn between demands on light, not between the two groups.

Design for one demanding condition often benefits everyone

Everyday precedents

Curb-cut effect

Pavement ramps cut for wheelchair users now serve prams and luggage.

Closed captioning

Made for Deaf viewers, now used by everyone.

Deaf Gain and DeafSpace

Deaf Gain

Deaf visual and spatial strategies are design knowledge in their own right.

DeafSpace beyond Gallaudet

Its principles have been extended to school environments.

Space sector

NASA-STD-3001

Human capability variation is built into design requirements.

ESA parastronaut project

Feasibility study for an inclusive European astronaut corps.

Design developed under a demanding condition routinely benefits all users.

Four objections to the transfer, and our responses

1 Cultural status

OBJECTION DeafSpace expresses Deaf cultural identity, so borrowing it risks a depoliticised appropriation.

RESPONSE **Design mechanisms are transferred, not cultural identity. The origin is acknowledged throughout.**

2 Evidence base

OBJECTION DeafSpace applications lack post-occupancy evaluation and quantitative verification.

RESPONSE **This gap is the point of entry. Expert consensus testing is joined to quantitative circadian science.**

3 Validity of the analogy

OBJECTION Lifelong perceptual reorganisation differs from short-term, situational crew constraints.

RESPONSE **The analogy is between demands on light. Experts rated the transfer plausibility of every item.**

4 One-size-fits-all

OBJECTION Universal design is criticised as a single standard solution.

RESPONSE **This is a specific design for one demanding condition, not a universal template.**

Three steps to build, test and rank the strategies

1 BUILD

Literature coding

- Content analysis, 10 core sources
- 198 coded strategies
- Mechanism transfer, not formal replication

43 candidate items

2 TEST

Modified Delphi consultation

- 11 valid experts, invited from 6 fields
- Item-by-item rating, two rounds designed
- Criterion: importance mean ≥ 7, CV ≤ 0.25

18 items retained

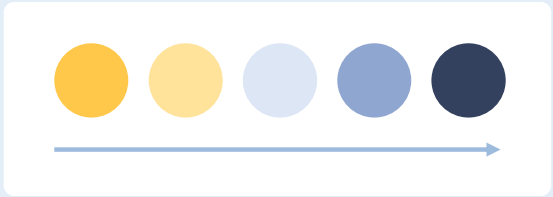
3 RANK

Entropy-weighted TOPSIS

- 4 criteria with objective weights
- Closeness to the ideal solution
- Equal thirds of the ranked list

3 priority tiers

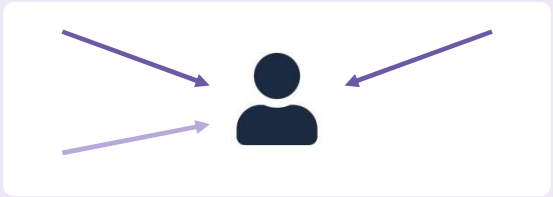
Dynamic lighting redefined along three axes



Temporal axis

Illuminance, spectrum and sequence are modulated with mission and circadian phase.

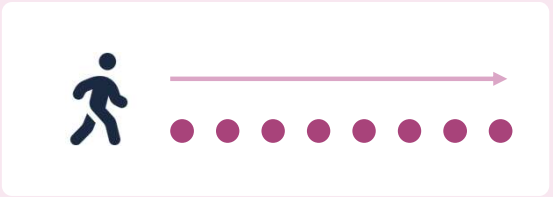
Basis: CIE adaptive lighting and integrative lighting



Spatial-compositional axis

Which objects are lit, from which directions, with what structure of brightness and background.

Basis: luminance distribution and perceived quality in lighting design



Continuity

Light information remains unbroken as people move, change posture and switch scenes.

Basis: environmental legibility and continuity of optical cues

STARTING POINT

Existing definitions of dynamic lighting cover the temporal axis only.

OBJECT OF STUDY

Interiors of pressurised lunar surface habitats for extended stays. Microgravity modules mark the boundary of extension.

From 198 coded strategies to 43 candidate items

26 sources and standards in the corpus

↓

10 core sources coded item by item

↓

198 original strategies

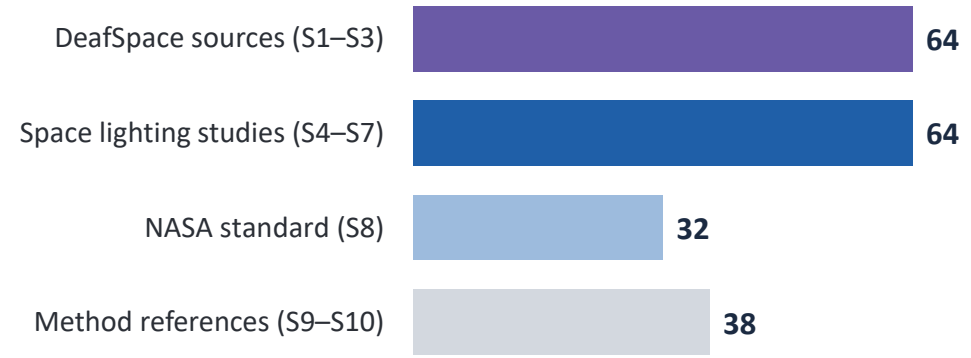
↓ *merged by mechanism*

43 candidate items

CODING RULE

Mechanisms are transferred, forms are not replicated.

Coded strategies by source group



EACH STRATEGY WAS RECORDED WITH

- original content
- translatable strategy
- mechanism of action
- application scenario
- evidence status
- transfer caveat

S1 Gallaudet Guidelines 2010 · S2 Edwards and Harold 2014 · S3 Cloete and Rout 2025 · S4 Caballero-Arce et al. 2012 · S5 Jiang et al. 2022 · S6 Rahman et al. 2022 · S7 Grant et al. 2024 · S8 NASA-STD-3001 Vol. 2 · S9 Ruiz et al. 2025 · S10 Tu and Zhou 2025

Candidate framework with 3 principles, 8 dimensions, 43 items

Principle I Perceptual continuity and spatial legibility	17 items
A — Visual communication and task information legibility	6 items
B — Spatial orientation, wayfinding and safe movement	6 items
C — Visual comfort, glare and material interfaces	5 items

Principle II Temporal and task adaptation, environmental regulation	15 items
D — Circadian and neurobehavioural adaptation	6 items
E — Psychological restoration, enrichment and time experience	4 items
F — Task- and scene-adaptive lighting	5 items

Principle III User control and resilient system integration	11 items
G — Control, individualisation and multimodal inclusion	5 items
H — Reliability, resource constraint and system integration	6 items

43 candidate items in total

PROGRESSIVE LOGIC OF ASSURANCE

Baseline perceptual guarantee → **Communication and wayfinding support** → **Adaptive health regulation**

Modified Delphi consultation, item by item

EXPERT PANEL

15 invited → **13** returned → **11** valid

Two returns were excluded. Every rating was marked N, meaning beyond the range of judgement.

SIX INVITED FIELDS

- Extraterrestrial architecture
- Space human factors
- Lighting engineering
- Visual ergonomics
- Inclusive design
- Behavioural health

EACH OF THE 43 ITEMS WAS RATED ON

Transfer plausibility	**1–9**	Does the transfer make sense?
Extraterrestrial importance	**1–9**	Does it matter on the Moon?
Engineering feasibility	**1–9**	Can it be built?
Clarity of wording	**1–4**	Is the item clearly written?

Processing recommendation for each item retain · revise · merge · delete · reassign

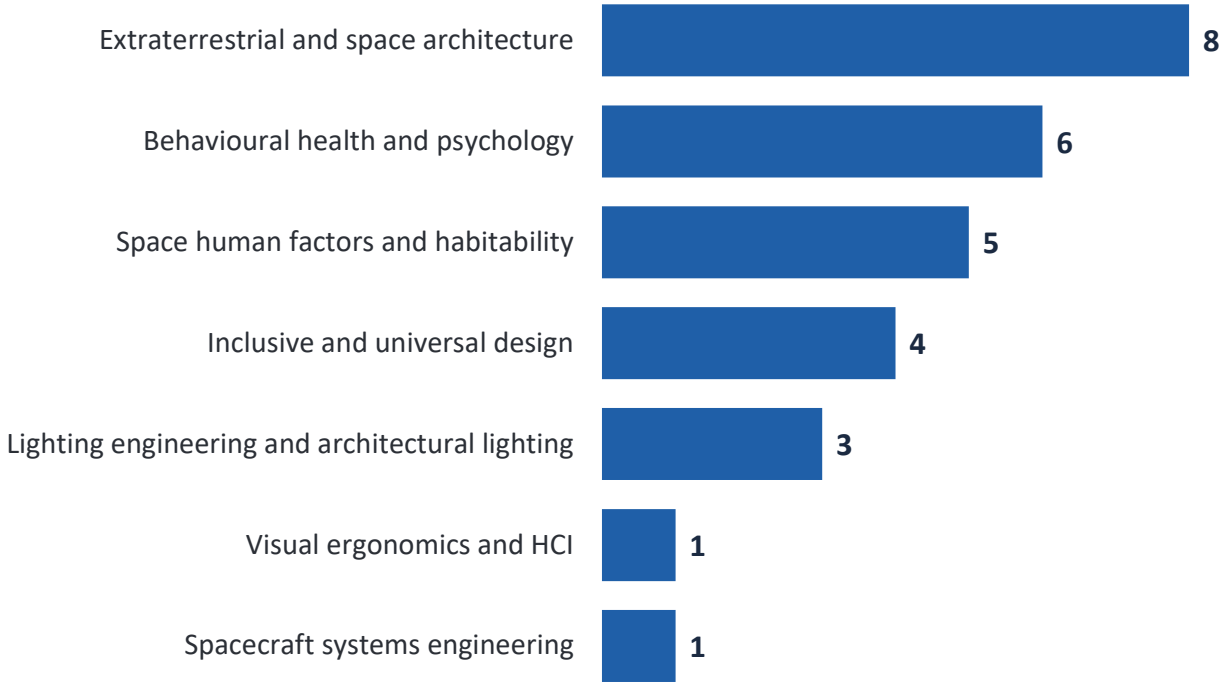
IMPORTANCE-CONSENSUS CRITERION

mean importance ≥ 7 and CV ≤ 0.25

Consensus refers to importance only. It does not imply agreement on feasibility or transfer plausibility.

A cross-disciplinary panel with acceptable authority

Fields of expertise, multiple responses, n = 11



9 of 11

experts hold a doctorate

Cr = 0.75

mean coefficient of authority, above the 0.70 acceptance level

Cs 0.63 · Ca 0.87

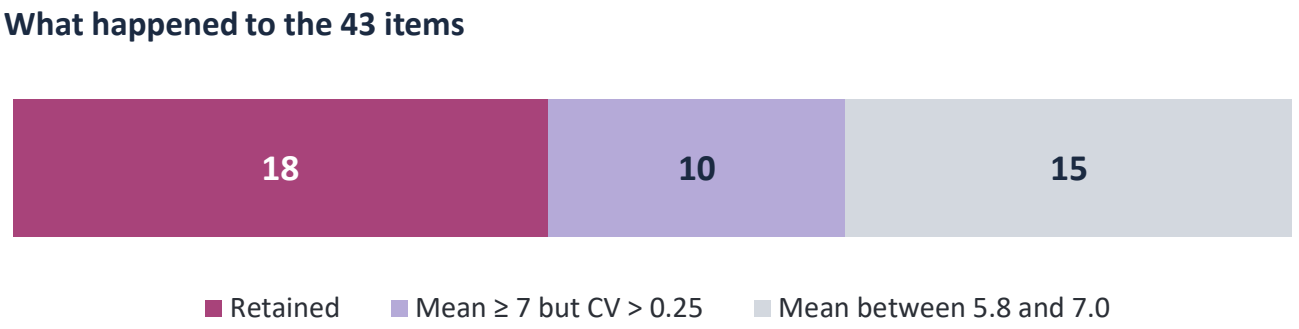
mean familiarity and mean judgement coefficients

One expert fell below 0.70. Individual values are descriptive and were not used to exclude anyone.

18 of 43 items reached importance-consensus in round one

18 / 43

items met the criterion in round one, which is 41.9%



0

items rejected outright. All 25 remaining items go to round two.

5.9%

of all valid processing votes were “delete”. The modal vote for every item was “retain”.

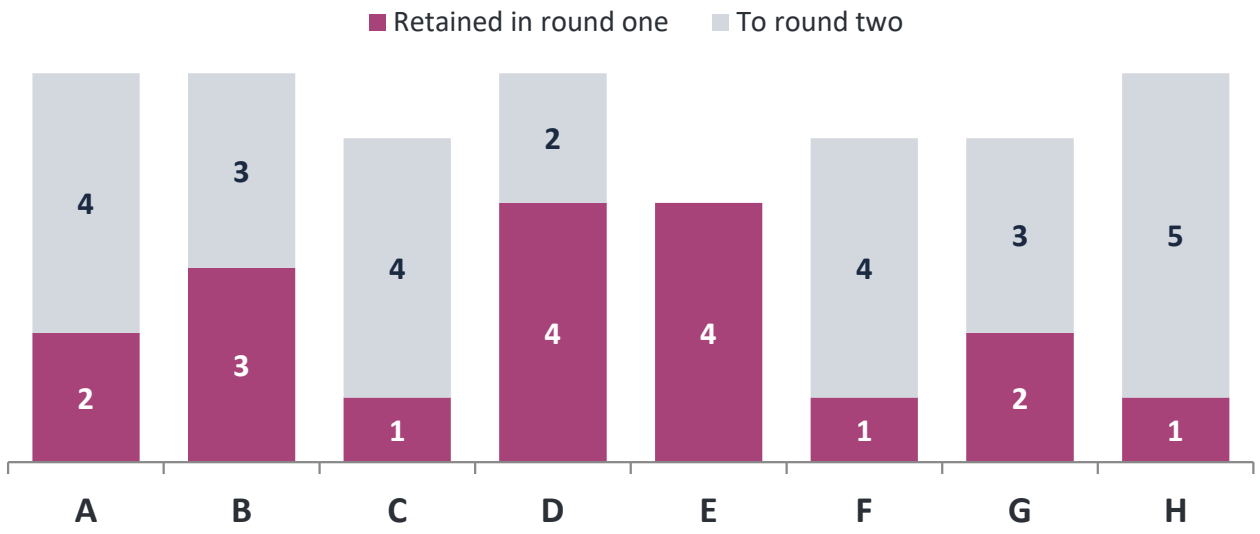
W = 0.219

Kendall’s W for importance, P < 0.001. Plausibility 0.183, feasibility 0.184. Significant but low to moderate, as usual in a first round.

Experts endorse the direction of the transfer. Disagreement centres on granularity and wording.

Consensus is strongest on circadian and psychological items

Items proposed and retained in each dimension



A Visual communication

B Orientation and wayfinding

C Visual comfort and glare

D Circadian adaptation

E Psychological restoration

F Task and scene modes

G Control and inclusion

H Reliability and integration

D and E

8 of 10 items retained. Circadian and psychological items converge first.

C, F and H

One item each. The direction is endorsed, the granularity is doubted.

Matches the standards

Circadian clauses are mature. Clauses on spatial composition remain weak.

Feasibility and consensus drive the ranking

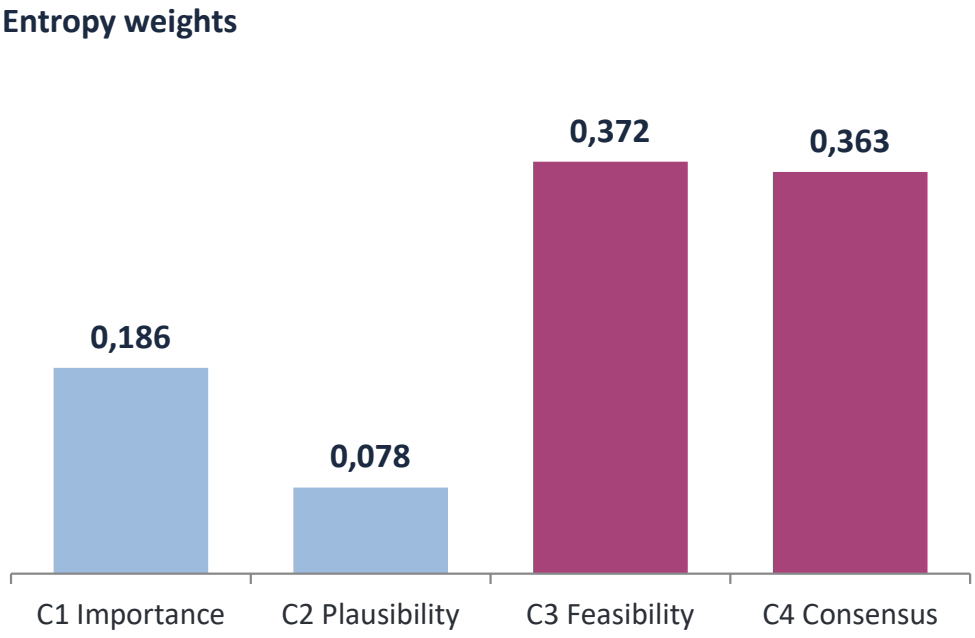
FOUR BENEFIT-TYPE CRITERIA

C1 **Extraterrestrial importance**
Delphi mean score

C2 **Transfer plausibility**
Delphi mean score

C3 **Engineering feasibility**
Delphi mean score

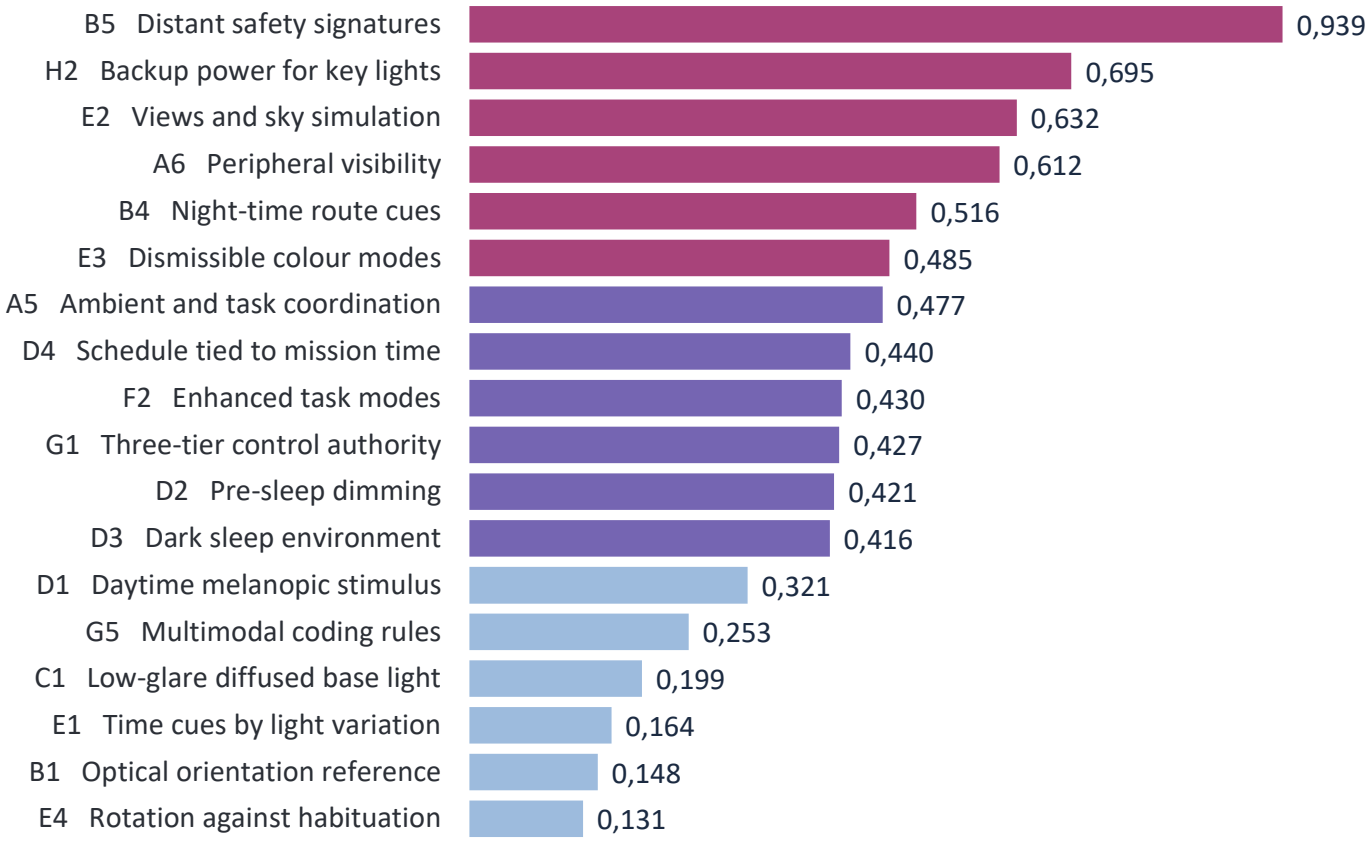
C4 **Degree of consensus**
1 minus the CV of importance



All 18 items already score high and close together on importance and plausibility, so these two criteria separate them least.

Entropy weighting sets each weight from the variability of the criterion. TOPSIS ranks items by relative closeness Ci to the ideal solution.

Priority ranking of the 18 retained items



RELATIVE CLOSENESS Ci, EQUAL THIRDS

High priority ranks 1 to 6

Medium priority ranks 7 to 12

Baseline priority ranks 13 to 18

ROBUSTNESS

Under three alternative weightings the rank correlation with this order is 0.969, 0.853 and 0.899. B5 stays first in every case.

TIER BOUNDARIES

E3 and A5 are only 0.008 apart. The tiers are an ordering, not three classes.

The six high-priority strategies in plain words

1 **B5**
Ci 0.939 · Principle I

Distant safety signatures

Safe havens, medical points, emergency equipment and critical hatches carry optical signatures identifiable at distance.

2 **H2**
Ci 0.695 · Principle III

Backup power for key lights

Local redundancy and independent power supply for critical-route, medical and emergency lighting.

3 **E2**
Ci 0.632 · Principle II

Views and sky simulation

Controlled external views, sky simulation or digital windows supplement naturalness and environmental variation.

4 **A6**
Ci 0.612 · Principle I

Peripheral visibility

Key personnel, adjacent modules and task objects stay visible at the periphery.

5 **B4**
Ci 0.516 · Principle I

Night-time route cues

Continuous low-melanopic route and obstacle cues during low-light and sleep periods.

6 **E3**
Ci 0.485 · Principle II

Dismissible colour modes

Low-dose chromatic enrichment for leisure, social and restorative settings, which users can dismiss.

The six items span all three principles. Item wording is abridged from Table 2 of the paper.

A priority group of six, then tiered implementation

High priority

B5 · H2 · E2 · A6 · B4 · E3

First-round priority group for inclusive lighting design

High importance with relatively high agreement and feasibility. An entry point for consolidating the dispersed lighting clauses of existing standards.

Provisional ordering, not a settled minimum specification

Medium priority

A5 · D4 · F2 · G1 · D2 · D3

Developed in step with functional zoning and mission planning

These items concern task-lighting coordination and circadian light scheduling.

Baseline priority

D1 · G5 · C1 · E1 · B1 · E4

Handled as constraints during system integration

Largely framework-level rules, such as multimodal coding following the three-tier control authority, not independent design items.

Implementation and resource allocation are organised by tier.

Three take-home messages

1 **Dynamic lighting is more than timing.** It also needs spatial composition and continuity.

2 **DeafSpace knowledge, transferred as mechanism, gained cross-disciplinary expert endorsement.** 18 of 43 items reached importance-consensus in round one, with a mean authority coefficient of 0.75.

3 **A first-round screened and provisionally ranked framework for crewed lunar surface habitats,** and a reusable route for transferring design knowledge between high-constraint environments.

Thank you !

BACKUP B1

The ranking is stable at the top, sensitive at the tier boundary

Weighting scheme	Spearman ρ	Top six under this scheme	Change against the reported top six
Entropy weights, four criteria	reported	B5 · H2 · E2 · A6 · B4 · E3	reference order
Equal weights, four criteria	**0.969**	B5 · H2 · E2 · A6 · A5 · E3	A5 enters, B4 leaves
Entropy weights, C4 removed	**0.853**	B5 · E2 · B4 · D4 · H2 · G1	D4 and G1 enter, A6 and E3 leave
Equal weights, C4 removed	**0.899**	B5 · E2 · H2 · A6 · G1 · D4	D4 and G1 enter, B4 and E3 leave

STABLE

B5 is first in every ordering. B5, H2 and E2 stay in the top six in every ordering. Each alternative keeps four to five of the reported six.

SENSITIVE

E3 at 0.485 and A5 at 0.477 are 0.008 apart, while D3 and D1 are 0.095 apart. The tiers are an ordering, not three classes.

C4, the degree of consensus, and C1 both derive from the importance ratings, which is why C4 was removed in two of the checks.

Ten items are important but not yet agreed

Mean importance of 7 or more, with CV above 0.25. They go to round two for rewording and regrouping.

Code	Item, abridged	Importance mean	CV
A1	Vertical illuminance on faces, hands and interlocutors	7.18	0.378
B2	Redundant encoding of routes, nodes, hatches and zones	**7.91**	0.262
C2	Integrated direct and indirect glare control	7.45	0.264
C3	Control schedule for reflectance, specularity and colour stability	7.18	0.277
C5	Limits on saturated colour, rapid change and visual clutter	7.45	0.264
F1	Baseline mode for general work and circulation	7.00	0.361
F5	Independent modes for emergency, egress and degraded systems	**7.91**	0.268
G2	Automatic control with status feedback, manual override and recovery	7.40	0.272
H1	Modular, calibratable lighting architecture	7.60	0.257
H3	Defined degraded operating states	7.18	0.270

B2 and F5 both reach 7.91. They failed on the spread of opinion, not on importance. No item was rejected outright.

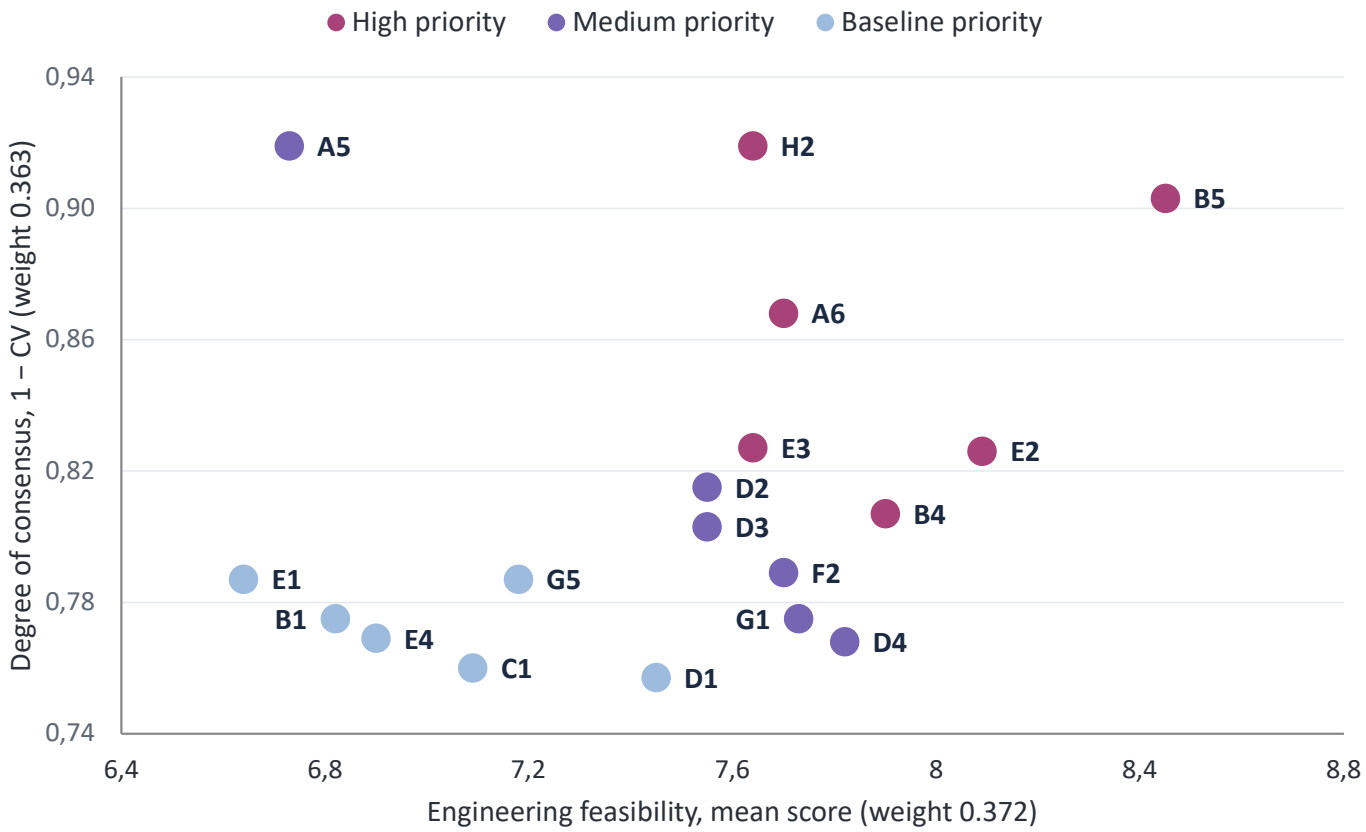
All 18 retained items with their scores

#	Code	Item, abridged	Imp.	Feas.	Ci
1	B5	Distant safety signatures	8.36	8.45	**0.939**
2	H2	Backup power for key lights	8.45	7.64	**0.695**
3	E2	Views and sky simulation	7.91	8.09	**0.632**
4	A6	Peripheral visibility	7.80	7.70	**0.612**
5	B4	Night-time route cues	7.40	7.90	**0.516**
6	E3	Dismissible colour modes	7.45	7.64	**0.485**
7	A5	Ambient and task coordination	8.36	6.73	**0.477**
8	D4	Schedule tied to mission time	7.73	7.82	**0.440**
9	F2	Enhanced task modes	7.45	7.70	**0.430**
10	G1	Three-tier control authority	7.73	7.73	**0.427**
11	D2	Pre-sleep dimming	7.18	7.55	**0.421**
12	D3	Dark sleep environment	7.64	7.55	**0.416**
13	D1	Daytime melanopic stimulus	7.64	7.45	**0.321**
14	G5	Multimodal coding rules	7.36	7.18	**0.253**
15	C1	Low-glare diffused base light	7.55	7.09	**0.199**
16	E1	Time cues by light variation	7.82	6.64	**0.164**
17	B1	Optical orientation reference	7.73	6.82	**0.148**
18	E4	Rotation against habituation	7.40	6.90	**0.131**

High Medium Baseline

Imp. and Feas. are mean importance and mean feasibility on a 1 to 9 scale. Ci is relative closeness.

Feasibility and consensus separate the 18 items



WHY A5 IS ONLY MEDIUM

A5 has an importance mean of 8.36 with very high agreement. Its feasibility is contested, with a mean of 6.73 and a CV of 0.371. It sits 0.008 below the high tier.

WHY B5 IS FIRST

B5 combines the highest feasibility, 8.45, with near-top agreement on importance. It stays first under every weighting tested.

Key formulas used in the evaluation

Coefficient of variation

$$CV_i = \frac{SD_i}{M_i}$$

Dispersion of opinion on item i. Retention needs CV of 0.25 or less.

Coefficient of authority

$$C_r = \frac{C_a + C_s}{2}$$

Ca is the judgement coefficient, Cs the familiarity coefficient. The panel mean must reach 0.70.

Kendall's W, corrected for ties

$$W = \frac{12\,S}{m^2(n^3 - n) - m\sum_{j=1}^{m} T_j}$$

S is the sum of squared deviations of rank sums, m the complete raters, n the 43 items.

Significance of W

$$\chi^2 = m\,(n-1)\,W$$

Chi-square test with n − 1 degrees of freedom, n being the 43 items.

Entropy weight

$$w_j = \frac{1 - E_j}{\sum_{j=1}^{k}(1 - E_j)}$$

Ej is the entropy of criterion j. More variable criteria receive more weight.

TOPSIS relative closeness

$$C_i = \frac{D_i^-}{D_i^+ + D_i^-}$$

Distances to the positive and negative ideal solutions. A larger Ci means higher priority.