Parametric study of speech privacy in semi-enclosed meeting pods

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Abstract
Overheard conversations are recognised as one of the most annoying sources of noise in the popular open plan layouts, which ends up in a lack of speech privacy and distraction. For addressing this problem, add-on market solutions are primarily reflectors and canopies installed in enclosed meeting pods or above fully open meeting furniture which are heavily relied on acoustical properties of materials. Through developing assorted matrices parametrically, this research identifies the governing geometric features of the canopies and reflectors in semi-enclosed meeting pods that impact speech privacy. Each solution was studied in an individual matrix and simulations were run in ODEON to examine each variable separately. The collective outcome offers preliminary design suggestions for improving speech privacy and implies that geometric design decisions can remarkably contribute to the auditory performance of the open interiors if considered and integrated into the design at the preliminary stages of the workflow.

Keywords: Parametric modelling, sound simulation, performance-driven design, speech privacy, integrated design

1 Introduction

Quite after the emergence of open plan working spaces, acoustical requirements were studied and defined to sustain employees' well-being and organisational efficiency, and productivity. Multiple standards were developed to establish a set of guidelines and methods to achieve the targets. However, in practice most likely the architectural design and the acoustical design are not integrated into a single workflow. Instead, with little to no exchange of information [1], acoustic experts are involved in most cases in the late stages of the design, or at the operational phase of the project [2]. In both scenarios, it is unlikely to modify the geometry substantially [3]. Thus, minor changes in the design features primarily in the form of appending new elements with different materials are proposed which are costly and less effective [4,5]. Acknowledging the size, form, and materiality as the three influential architectural design principles reveals the strong mutual connection between architecture and acoustics [6]. This implies that the soundscape is being formed from the onset of the design concept and it is deeply rooted in every design decision.
The need for transformative steps to integrate architectural intervention in the acoustic design of working spaces is now marked with greater reasons. End-user research and empirical studies in recent years show growing attention to the aesthetics of the working environments and furniture and demand for visually appealing design with adequate visual connection and a sense of privacy [7,17]. In addition, the recent movement of performative architecture [8,9,10], supported by the advancement in CAD modelling and the emergence of parametric design, raised the question of how sound performance can become a form generator at the conceptual stage. Parametric modelling and generative design with real-time simulation, analysis, and feedback can countervail the shortfall of know-how knowledge of acoustics in architecture. However, despite

this recent interest, still, the application of acoustic performance-based design is limited in practice [3,11]. The use of sound absorption materials remains the popular solution to the acoustic problems of open plan offices [12], despite its failure in meeting the conflicting acoustic requirements of having speech intelligibility within a space and maintaining speech privacy between the spaces [6,13,14]. Applying a single method of sound-absorbing surfaces seems insufficient to calibrate the acoustic performance. In the meeting spaces, absorbent materials decrease the reverberation time and increase the speech intelligibility within the space, more often beyond necessity. Given the inverse relationship of speech intelligibility and speech privacy [15,16], a crystal-clear conversation is more exposed to the risk of overhearing between the spaces. In small meeting rooms, since the major contributor to speech intelligibility is the direct sound [26], speech privacy should become the priority of the design [13,17]. Therefore, an alternative to absorption has to be considered, that is to control the sound propagation by capturing the sound inside the space for a longer period until it is exhausted. Market-oriented cubic pods or furniture designed fully enclosed or widely open with acoustic materials to absorb the sound fall short of taking this approach into account. Besides the pods, a wide range of clouds, canopies, baffles, and panels were also introduced by well-known industries such as Hermann Miller Inc. Haworth, Steelcase, buzzispace, etc. including sound performative light pendants and floating clouds and panels in various patterns such as pleated, gridded or 3D patterned and in multiple shapes with or without holes. These products are mostly studied in literature and applied in practice for their influence on the reverberation time of the open working environments and reducing the noise level while their effect on speech privacy has not been fully addressed.

2 Objectives

While in practice the acoustic design of the open plan workplaces is primarily leaning towards the sound properties of the materials [12], the present paper proposes a new approach to control sound propagation with the help of the geometry of the boundaries. Taking advantage of parametric modelling in producing a heterogeneous collection of iterations, this paper sheds light on the efficiency of a performance-driven architectural design that improves the speech privacy of a meeting pod in addition to the material consideration.
A semi-enclosed meeting pod with high partitions is studied as an appropriate solution to offset the drawbacks of both extreme ends: low-partition pods or open meeting furniture that offer little to no privacy as opposed to the go-to default enclosed cocooning solutions that defy the open plan layout concept.
While this paper is a continuum of series of investigations into the topic [13,18], it aims to analyse canopies and reflectors in an integrated design as the two most sought-after approaches in the market for designing and retrofitting the open plan offices and meeting rooms.

3 Methodology

3.1 Analysis parameter and modelling technique

Speech Transmission Index (STI), introduced in 1980 [19], is an objective indicator of the quality of the speech transferred to the listener that can be applied to predict and measure speech intelligibility and speech privacy [20]. Among all parameters of assessing speech privacy, STI, for its A-weighted filtering, is believed to be tied strongly to the human perception of speech privacy [21]. Therefore, it is selected as an objective speech privacy metric in this paper.
The methodology developed for this study is a comparative analysis. Since sound performance is highly dependent on numerous interactive macro and micro spatial parameters, any trivial changes in the building environment including materiality, geometry, structure, furniture, occupancy, temperature, and humidity, etc. can cause a dramatic change. Therefore, in the interest of achieving some general conclusions in each matrix of study all parameters including materiality were kept constant. Iterations were generated with a parametric tool to ensure consistency in 3D modelling and to have absolute control over geometrical attributes such as

volume, length, and angle which would be otherwise hard to govern. In addition, parametric tools can push beyond the limitations of the number of iterations that can be generated by traditional 3D modelling software.

All iterations were modelled in the Grasshopper, a parametric tool for the Rhinoceros 3D. A symmetrical cubic shape geometry was selected as the basis for the open plan office. The finished floor-to-ceiling height is 3.3 metres with a total area of 900 square metres in the plan. The semi-enclosed pod is placed in the centre with the consistent 50 cubic metres volume and the average volume-to-surface-area ratio of 1 metre. The partitions of the pod are extended up to 0.3 metres below the finished ceiling, allowing a 0.3 metres gap between the finished ceiling and the pod's top edges. The pod in all simulations is hexagonal in plan, but with three overall variations of convex, concave and flat surfaces. The symmetry in the pod and the open plan office was maintained in all iterations to minimise the effects of the mutual interaction of the pod and open working environment on the acoustic performance of both spaces. However, the reciprocal relationship between materiality and overall geometry was investigated, and more details on this can be found in previous studies [13,18].

3.2 Sound simulation setup

Few widely applied geometrical acoustic simulation tools are available including CATT-Acoustic, EASE, Pachyderm, Ansys, I-simpa, SoundPlan, etc. However, in this study, ODEON, a hybrid commercial room acoustic software is selected as one of the most reliable and widely reviewed software in literature [22,23]. Surfaces were assigned identical absorption coefficient values in all simulations as presented in Table 1. The value of 0.05 was also given as a scattering coefficient to all surfaces.

Table 1– Absorption coefficients of the pod and office surfaces

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	α(w)
Ceiling	0.30	0.30	1.00	1.00	1.00	1.00	0.97	0.97	1.00
Floor	0.04	0.04	0.04	0.08	0.12	0.10	0.10	0.10	0.10
wall	0.10	0.10	0.05	0.06	0.07	0.09	0.08	0.08	0.10
Pod	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

The sound source was set in the centre of the pod at the average height of a seated person, 1.2 metres above the floor. The SPL values of the sound source applied in this study are listed in Table 2.

ISO 3382-3 [20] recommendation for having an omnidirectional sound source was adopted in this study. However, since speech is inherently directional, a comparative simulation was performed to explore the outcome differences if the real environment was about to be simulated.

Figure 1 presents the STI maps with omnidirectional versus directional sound sources. It is observed that except for the rear-facing positions which benefitted from more speech privacy, there is little to no difference in the speech privacy of the listening areas facing the speaker.

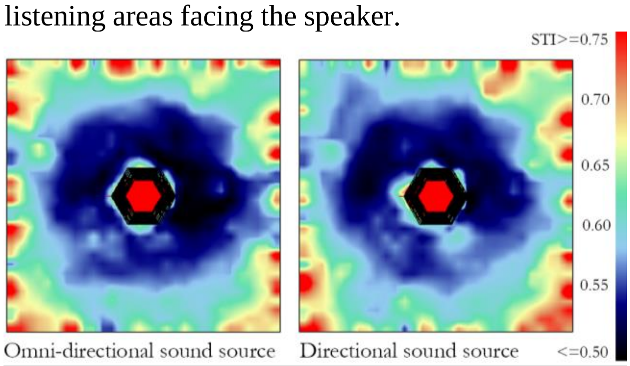

Figure 1– STI maps with directional vs. omnidirectional sound source

Table 2 – Omnidirectional sound source level applied in this study

Frequency (Hz)	125	250	500	1000	2000	4000	8000	Total power	Total SPL at 10 m
SPL (dB)	60.9	65.3	69	63	55.8	49.8	44.5	71.8 dB	40.8 dB
								68.4 dBA	37.4 dBA

3.3 Results interpretation

ISO 3382-3 [20] suggests STI as the primary measure to evaluate speech privacy. However, there are slight disagreements on the thresholds and definitions of speech privacy over the entire range from 0 to 1. ISO 3382-3 [20] defines the privacy zone when STI drops below 0.2 and the distraction zone when STI is below 0.5, whereas, in ISO 60268-16 [24], with STI above 0.75, there is no privacy and with STI below 0.6 reasonable speech privacy is provided. The normal speech privacy in this standard is ranged from 0.3 to 0.45 with excellent privacy in areas with STI below 0.3. In an experiment for exploring the human perception of privacy in a real environment, the threshold of 0.6 STI corresponded more to the subjective analysis of the non-distracting areas with an acceptable level of privacy [25]. Therefore, in this study STI of 0.6 is considered the borderline of having an acceptable level of speech privacy.

4 Results and Discussion

4.1 Matrix A: Suspended ceiling with partial coverage

Overhead canopies are extensively applied in open plan offices to create micro soundscapes in areas where conversations are likely to happen. They come in various shapes and patterns and they can function as both sound absorbers and light pendants. They are mostly applied to absorb the sound and decrease the RT value. However, for semi-enclosed meeting pods with high partitions, further study is required to investigate the impact of suspended canopies on improving speech privacy. Two types of canopies are simulated in this study (Figure 2) each in combination with three pods varied in section: Flat, convex, and concave pods.

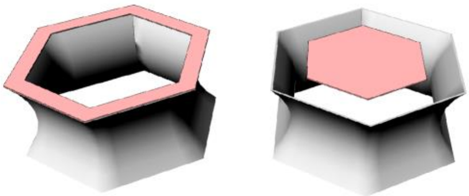

Figure 2 – Two approaches for partially covering the ceiling, donut style and suspended central canopy

In Figure 3, expectedly, it is illustrated that as the size of the suspended central canopy gets smaller and the gap between canopy and pod widens the STI increases in all three types of the pod. However, interestingly the matrix indicates that the impact of a central canopy on both concave and flat pod counters the significant STI improvement that the central canopy brings to the convex pod. This implies the effectiveness of adopting a central canopy just over a convex pod. While in a convex pod with no overhead canopy only 0.5% of the office area has STI below 0.6, this figure soars to 41% when the void between the pod's top edges and canopy's edge is 50 cm. When the canopy shrinks and the gap starts to open up the percentage of areas with STI under 0.6 falls quickly to 17% with only a 20 centimetres increase in the gap. With a metre distance between the edges of the canopy and pod, this value drops to only 8% which is 16 times better than a convex pod with no canopy and 5 times less effective than a convex pod with a larger overhead canopy. Therefore, it

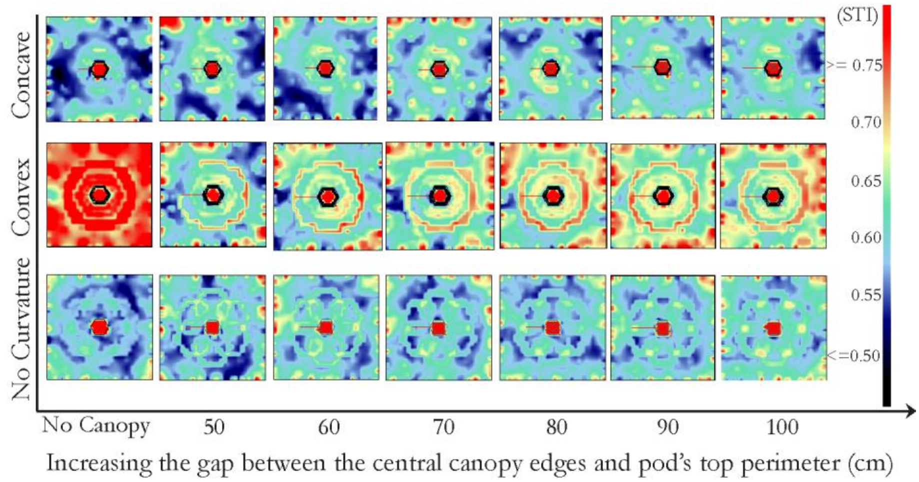

Figure 3 – Matrix A-1, Exploring STI maps of three types of the pods with suspended central canopy of various sizes

can be concluded that integrating a suspended central canopy would be more beneficial to pods with an overall convex shape when there is no architectural alternative to change the geometry. The size of the canopy must be reasonably large to allow a minimum gap and maximum advantage that outweighs the cost. If acoustic performance drives the design at early stages, then the convex form should be avoided most. That being the case the central canopies over the high-partitioned semi-enclosed flat and concave pods would not further enrich speech privacy.

Going over and above that, an increase in the STI of the open plan office can be observed when adding a central canopy with a sound absorption coefficient equal to or less than the absorption coefficient of the ceiling. This rather contradictory finding might be interpreted as being the result of expanding the edges, where the diffraction happens, without adding absorption value. The more edge diffraction happens, the earlier sound releases in the open plan office. Edge diffraction can interrupt the regular reflections in the pod and fewer sound rays would reflect back to the pod. Limiting the edges of the design and thus reducing diffraction would help to control the sound reflection paths and to trap the sound waves inside the pod for a more extended time.

Modifying the partial ceiling design from a central canopy to a donut-shaped that wraps around the top edges can resolve the problem caused by the increased length of edges. It also gives an advantage of covering the areas where according to the 3D animated investigative ray tracing in ODEON most sound waves are observed to escape. As illustrated in Figure 4 the value of STI has dropped in all three types of the overall geometries when a donut-shaped partial ceiling is added. This implies that generally, STI improvement in this form of coverage exceeds the speech privacy that canopy-style ceiling offers.

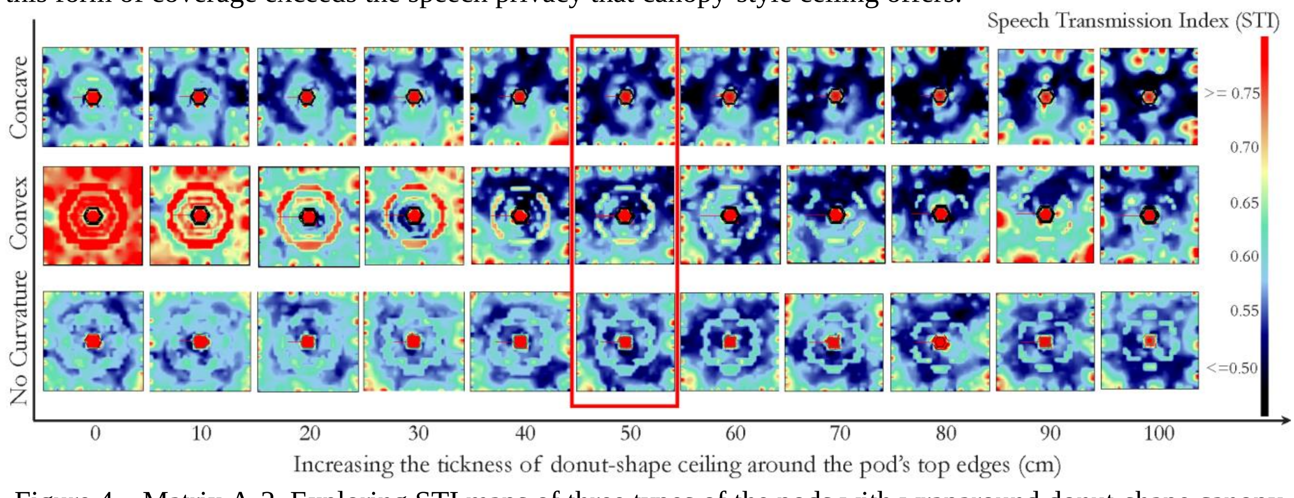

Figure 4 – Matrix A-2, Exploring STI maps of three types of the pods with wraparound donut-shape canopy of various sizes

It should be stressed that the simulation set up in this study is compatible with the acoustic standards of the open plan offices and the requirement for having an absorbent ceiling. Changing the context to an old fashion working space with little to no sound absorptivity in the ceiling would dramatically affect the results.
A gradual increase in the size of the donut-shaped ceiling leads to a rapid decrease in STI. It levels out when the partial ceiling spans half a metre. The value of adding donut-shaped coverage around the top, up to 50 cm in length, is substantiated by 13%, 75%, and 23% increases in the areas with STI below 0.6 in the concave, convex and flat pods respectively. By adding a 50 cm partial ceiling around the edges still, the improvement in speech privacy is achievable but to a smaller extent. 10%, 8.5%, and 1% more office areas will be placed in a non-distractive zone when adding wraparound coverage to concave, convex, and flat pods respectively.
These results suggest solutions when there are no alternatives to the overall design geometry. For instance, with only 50cm coverage around the edges on the top, the convex pod can acoustically function very close to the concave pod, if not equal. It can be observed from the matrices that the convex pod benefits most from both types of partial ceiling add-ons. However, overall, the wraparound donut-shape ceiling performs distinctly better than the suspended central canopy ceiling, which is more common in practice. A summary of figures from CDF graphs is presented in Table 3.

Table 3 – Summary of the CDF graphs for STI for both types of partial ceiling

Size of the gap between the central canopy and pod in cm			No canopy	50	70	80	100
Percentage of STI (CDF graph)	STI<=0.6	Concave	69	60	53	53	52
		Convex	0.5	41	17	12.5	8
		No curve	51	55	51	48	40
	STI<=0.5	Concave	2.5	0.78	0.2	0	0
		Convex	0	0.55	0.2	0	0
		No curve	0.2	0.2	0.1	0	0
size of donut-shape coverage in cm			0	40	50	60	100
Percentage of STI (CDF graph)	STI<=0.6	Concave	69	72	82	77.6	77.7
		Convex	0.5	66	75	75.2	75
		No curve	51	62	75	72	70
	STI<=0.5	Concave	2.5	12.5	12.5	14.6	22.6
		Convex	0	8.5	8.5	8	8.5
		No curve	0.2	0.2	0.8	0.6	0.5

4.2 Matrix B: Alteration in the angle of incidence (reflectors)

Excluding the direct sound, first-order reflections are the most significant contributors to speech intelligibility [16,27,28]. The angle of incidence when the sound first strikes the pod and the first reflection happens is critical according to the raytracing technique. Therefore, another matrix is developed to investigate the early reflections' path by studying the angle of incidence as an influential parameter.
Two possible approaches to change the angle of incidence are studied in this matrix: global modification to the pod's geometry or appending wraparound reflectors to a portion of the pod that corresponds to the height of the sound source. The bottom row of the matrix in Figure 5 illustrates changes in the angle of incidence

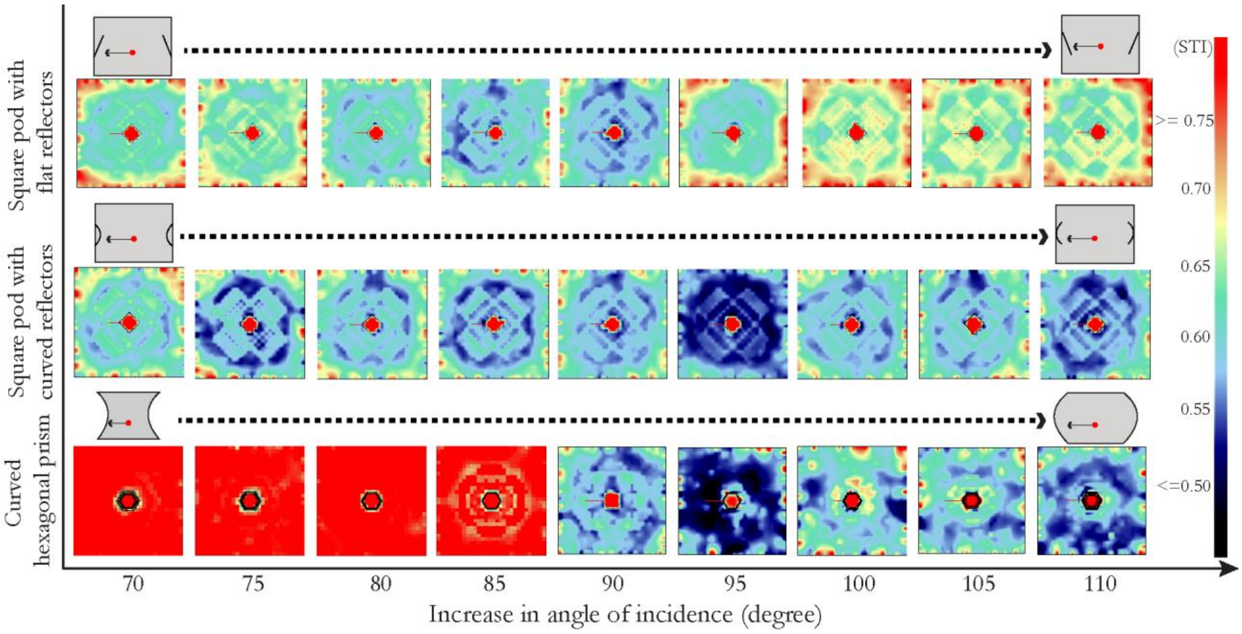

Figure 5 – Matrix B, Exploring the influence of angle of incidence on STI in three variations

from 70 degrees to 110 at the approximate height of a sitting person (120 cm), by transforming curvature gradually from convex to a concave shape. In the second row, the all-embracing curvature of the first row is downscaled to only cover one-third of a simple square pod's surface at the height of the sound source. The angle of incidence was changed from 70 to 110 degrees through the change of the reflector's curvature.
In the last top row of the matrix, the angle of incidence is changed by rotating a flat reflector from 70 to 110 degrees. The flat reflectors, similar to the curved reflectors in the second row, cover one-third of the pod's height in the middle.
Broadly speaking, this matrix confirmed the previous findings that the convex shape is ineffectual in providing an acceptable level of speech privacy in the open plan office. In the bottom row, the STI dramatically decreased when the angle of incidence reached 90 degrees in a flat pod and dropped the most when the angle of incidence was increased to 95 degrees in a concave pod. A similar peak in speech privacy can be observed when the angle of incidence reached 95 degrees in a simple flat square pod with curved reflectors in the second row of the matrix. Comparing the first two rows interestingly reveals that downscaling the convex geometry from the overall shape to reflector significantly improves the speech privacy of the open plan office in the second row. This result suggests that the flat surfaces of the pod can partially compensate for the scattering characteristics of the convex reflectors and hold the sound inside for a greater period compared to the pod that is globally shaped with convex curvature.
In the third row, improvement in speech privacy when the angle increases from 70 to 90 degrees are still apparent. However, there is a reverse trend when the reflector creates an angle of incidence of more than 90 degrees. STI begins to increase when the angle of incidence rises from 90 to 110 degrees. This pattern was anticipated, since with a flat reflector unlike the curved one there is no reversible barrier element to change the reflection path back to the pod when it is directed outside with an obtuse angle. Alternatively stated, flat reflector lacks the embracing characteristic of the concave reflector. Instead, it tends to accelerate the sound release when the angle is obtuse.
By designing an appropriate geometry that responds to the effects of angle of incidence, the STI can be dramatically decreased from 0.7 in a convex pod to 0.45 in a pod with either an overall concave shape or partially covered by concave reflectors with 95 degrees angle of incidence.
In further developing the investigation, a combination of flat reflectors with concave and convex pods has also been studied. A wraparound flat reflector with a right angle of incidence was added to both concave and convex pods and was compared to each other in Figure 6. Consistent with the previous results, the concave pod with no reflector outperforms all three other options. However, the speech privacy of convex geometry

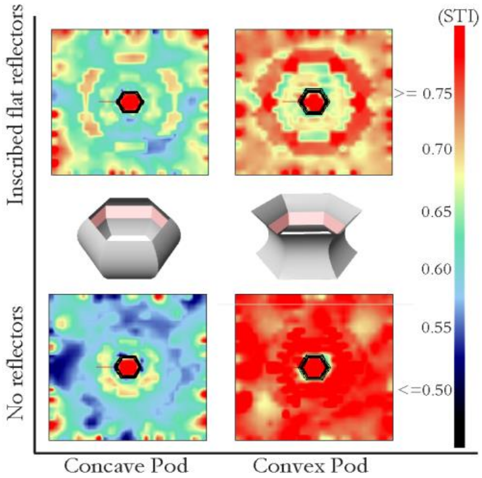

Figure 6 – The impact of flat reflectors on STI of concave and convex pod

can be noticeably improved by appending wrap-around flat reflectors. The reflector can disrupt the continuous reflections inside a concave pod while it can assist in holding the sound inside a convex pod for an extended period before releasing it into the open plan office.

In practice restrictions such as cost, limited space, design specifications, and fabrication process may limit the alternatives. Therefore, it becomes significant for designers to be aware of the counterbalanced solutions like proper reflectors and/or partial ceilings to offer an acceptable level of performance in an integrated design. An example of such a workflow can be found in previous studies where the design of a semi-enclosed meeting pod was calibrated to accommodate fabrication limitations and a partial ceiling was considered in an integrated double-skin design early at the design stage [29,30].

Since the findings are based on the ray-tracing simulation results can be varied with any trivial changes in the context, geometry, size, volume, and materiality. The conclusions from such analyses therefore should be interpreted with the utmost caution. The findings should be considered as an informative guideline and the comparison methodology introduced in this research can be applied to offer proper solutions for any design scenario.

5 Conclusions

This paper presented an architectural investigation on improving the speech privacy of semi-enclosed meeting pods through developing parametric matrices of iterations in a coherent approach.

The common acoustic strategy in practice is the application of sound absorption materials to achieve a defined standard reverberation time. Low reverberation time increases speech intelligibility. While high speech intelligibility is desirable for employees' health, comfort, and productivity, in open plan offices with open meeting areas or semi-enclosed meeting pods it eases unintended and effortless eavesdropping and puts the meeting privacy at risk. For addressing this conflict, it is suggested to create a micro soundscape within an open plan office with the higher reverberation time, less speech intelligibility but more speech privacy. While low reverberation is ideal for open working spaces, a micro-auditory environment with higher reverberation is more required in the meeting pods. This can happen through an integrated architectural design and reconsideration of the choice of materiality, from the pure absorbent to a combination of reflective and absorptive surfaces. The reflective micro soundscape of the meeting pod decreases the speech intelligibility inside the pod, yet offers more speech privacy, which is the priority for a small meeting space. Broadly speaking, in the design of a semi-enclosed meeting pod with the focus on achieving the highest possible speech privacy, the proposed geometry of the pod should be capable of holding the sound inside, instead of expediting sound release and propagation in open layout space.

In this paper, two market-favoured approaches for designing and retrofitting meeting spaces in open plan offices were studied: canopies and reflectors. While both strategies are widely applied in practice for reducing RT and noise and increasing speech intelligibility, in this research they were examined for their efficiency in improving speech privacy. The wraparound donut-shape ceiling was almost twice as efficient as the suspended central canopy of the same size in producing speech privacy in convex pods. It also helps to decrease the STI in the concave and flat pods but with a much lower rate compared to the convex pod. The same results were observed when appending or integrating reflectors in three different pods with concave, convex, and flat surfaces. A maximum of 0.25 reduction in STI was reported in a convex pod when the angle of incidence reached 95 degrees. The results were quite similar in two methods of changing the angle of incidence: gradually modifying the overall geometry from convex to concave to achieve 95 degrees of angle of incidence or placing a reflector with that specific angle inside the pod. A significant observation is that if the pod's overall geometry happens to be more enfolding than the shape of the add-on reflector, the reflection pattern can be interrupted and the sound would be released in the open plan office much quicker.
With geometrical solutions, a convex pod can perform quite as efficiently as a concave pod, when the design options are limited. This offers much flexibility and creativity in designing ground-breaking and aesthetically pleasing performance-driven prototypes of meeting pods in the future.

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References

[1] Takenaka, T.; Okabe, A. A Computational Method for Integrating Parametric Origami Design and Acoustic Engineering, *eCAADe 2013*, Delft, Netherlands, September 18-20, pp 289-295.

[2] Sheridan, T., Van Lengen, K. Hearing architecture: Exploring and designing the aural environment, *Journal of Architectural Education*, 57(2), 2003, 37-44.

[3] Badino, E.; Shtrepi, L.; Astolfi, A. Acoustic performance-based design: a brief overview of the opportunities and limits in current practice, *Acoustics, Multidisciplinary Digital Publishing Institute*, 2 (2), 2020, pp. 246-278.

[4] Salter, C.; Powell, K.; Begault, D.; Alvarado, R. Case studies of a method for predicting speech privacy in the contemporary workplace, *UC Berkeley: Center for the Built Environment*, 2003.

[5] Sarwono, J.; Larasati, A. E.; Novianto, W. N. I.; Sihar, I.; Utami, S. S. Simulation of several open plan office design to improve speech privacy condition without additional acoustic treatment. *Procedia-Social and Behavioral Sciences*, 184, 2015, 315-321.

[6] Roy, K. P.; Snader, A. L. Acoustics and sustainable design in exposed structures, *Journal of the Acoustical Society of America*, 123(5), 2008, p 2970.

[7] Anjum, N.; Paul, J.; Ashcroft, R. The changing environment of offices: A challenge for furniture design, *Design Studies*, 26(1), 2005, pp 73-95.

[8] Kolarevic, B.; Malkawi, A. *Performative architecture: beyond instrumentality*. Routledge, e-book, 2005.

[9] Menges, A. Manufacturing performance. *Architectural design*, 78(2), 2008, pp 42-47.

[10] Oxman, R. Performance-based design: current practices and research issues. *International Journal of Architectural Computing*, 6(1), 2008, pp 1-17.

[11] Peters, B. Acoustic performance as a design driver: sound simulation and parametric modeling using Smartgeometry, *International Journal of Architectural Computing*, 8(3), 2010, pp 337-358.

[12] Rychtarikova, M.; Nijs, L.; Saher, K.; Van der Voorden, M. Architectural guidelines for living rooms, classrooms, offices, sports facilities and restaurants, *InterNoise*, Prague, Czech republic, August 22-25, 2004, pp. 1169-1176.

[13] Alambeigi, P.; Burry, J.; Cheng, E. Investigating the effects of the geometry on speech privacy of semi-enclosed meeting spaces. *SimAUD 2017*, Toronto, Canada, May 22-24, 2017, pp. 1-8.

[14] Roy, K.; Snader, A. Acoustic design for 'green' buildings, *International Congress on Acoustics (ICA)*, Madrid, Spain, September 2-7, 2007, pp 4244-4249.

[15] Bradley, J. S.; Sato, H.; Picard, M. On the importance of early reflections for speech in rooms, *The Journal of the Acoustical Society of America*, 113(6), 2003, pp 3233-3244.

[16] Bradley, J. S.; Apfel, M.; Gover, B. N. Some spatial and temporal effects on the speech privacy of meeting rooms, *The Journal of the Acoustical Society of America*, 125(5), 2009, pp 3038-3051.

[17] Alambeigi, P.; Burry, J.; Zhao, S.; Cheng, E. A study of human vocal effort in response to the architectural auditory environment, *Architectural Science Review*, 63(3-4), 2020, pp 262-274.

[18] Alambeigi, P. Shape the Sound in Space: Design to Refine Speech Privacy Perception, Doctoral dissertation, *Swinburne University of Technology*, 2020.

[19] Steeneken, H. J. M.; Houtgast, T. A physical method for measuring speech-transmission quality, *The Journal of the Acoustical Society of America*, 67(1), 1980, pp 318-326.

[20] EN ISO 3382-3: *Acoustics — Measurement of room acoustic parameters — Part 3: Open plan offices*, Geneva, 2012.

[21] Robinson, M.; Hopkins; C.; Worrall, K.; Jackson, T. Thresholds of information leakage for speech security outside meeting rooms, *The Journal of the Acoustical Society of America*, 136(3), 2014, pp 1149-1159.

[22] Howarth, M.; Y. Lam. An assessment of the accuracy of a hybrid room acoustics model with surface diffusion facility, *Applied Acoustics*, 60(2), 2000, pp 237-251.

[23] Vorländer, M. International round robin on room acoustical computer simulations. *15th Intl. Congress on Acoustics*, Trondheim, Norway, June 26-30, 1995, pp. 689-692

[24] International Standard IEC 60268-16: *Sound system equipment–Part 16: Objective rating of speech intelligibility by speech transmission index*, Geneva, 2011.

[25] Alambeigi, P.; Zhao, S.; Burry, J.; Qiu, X. Complex human auditory perception and simulated sound performance prediction: A case study for investigating methods of sound performance evaluations and corresponding relationship. *CAADRIA 2016*, Melbourne, Australia, 30 March-2 April, 2016, pp 631-640.

[26] Arweiler, I.; and J. M. Buchholz. The Influence of Spectral Characteristics of Early Reflections on Speech Intelligibility, *The Journal of the Acoustical Society of America*, 130 (2), 2011, pp 996–1005.

[27] Lochner, J; Burger, J, The influence of reflections on auditorium acoustics. *Journal of Sound and Vibration*, 1(4), 1964, pp 426-454.

[28] Bottalico, P.; Graetzer, S.; Hunter, E. J. Effects of speech style, room acoustics, and vocal fatigue on vocal effort, *The Journal of the Acoustical Society of America*, 139(5), 2016, pp 2870-2879.

[29] Alambeigi, P.; Chen, C.; Burry, J.; Cheng, E. Shape the Design with Sound Performance Prediction. *CAAD Futures*, Istanbul, Turkey, July 12-14, 2017, pp 115-127.

[30] Alambeigi, P.; Chen, C.; Burry, J. Negotiating sound performance and advanced manufacturing in complex architectural design modelling, *Humanizing Digital Reality, Springer*, 2018, pp 627-638.