MACH ACOUSTICS

Keynsham Town Hall

OPEN PLAN OFFICES:
ROOM ACOUSTIC DESIGN REVIEW

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OPEN PLAN OFFICE – ROOM ACOUSTIC DESIGN REVIEW

Revision	Description	Issued by	Issue date
	First issue	Andrew Rickard	15/04/2013

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Introduction

MACH Acoustics have been requested by Willmott Dixon to review the likely acoustic performance of the open plan office spaces (2) at Keynsham Town Hall. The focus of MACH Acoustics review has been to assess proposed finishes, discuss the effects of screens between desks and analyse the potential of varying levels of acoustic treatments.

MACH Acoustics Design Approach

The overall performance of an office space is a function of a number of factors of which acoustics is one. In MACH Acoustics view, all factors affecting a given space need to be considered. This report therefore aims to provide the design team and users of the building with sufficient information such to decide upon the extent of acoustic treatment that will be present in the finished building.

MACH Acoustics approach has therefore been to explain/ demonstrate the effects of various forms of treatments. The evidence in this report is intended to be used by others to make an informed decision as to which is the best way forwards.

Design Targets

At this stage, it is important to recognise that there are few acoustic standards for which an open plan office should be designed to. The balance of acoustics against other factors is typically left down to the client and design teams. However a reverberation time limit of 1.2 seconds is included within the Employers Requirements, put together by Max Fordhams.

The image to the top right (1) provides an example of an office design which meets its clients expectations and requirements. A good acoustics consultant would have advised that the office space (1) as a minimum, required some level of soft treatment to the soffits. Treating the solid concrete wall would also have formed part of the acoustics recommendation. Placing screens between desks would be the next element of design advice given.

However, MACH Acoustics has studied this office extensively and worked closely with the office users, who have all clearly indicated that they are more than happy with all aspects of this space, both visually and acoustically.

It is therefore concluded that there is no right or wrong way to design an open plan office space and that the requirements and merits of different strategies need to be considered as a whole. One should take care and potentially not strive for the very best acoustic performance.

1

2

Measurements and Assessments

MACH Acoustics are not looking to answer the question as to whether the right acoustic approach to date has been taken or not. Instead, we are aiming to highlight and more importantly explain/ demonstrate the difference between design strategies and acoustic treatments.

To do this, a Ray Tracing model (1) has been used as a key design tool.

Ray Tracing models have been built (1) using CATT Acoustics. This model is available upon request. CATT Acoustics models a space by sending out thousands of rays representing a specified sound source. This software is exceptionally accurate due to the fact that the position of acoustic treatments are considered. This software also provides a wide range of parameters including the decay of sound over distance, reverberation times and speech intelligibility across the office floor. CATT modelling can also be used to assess the spread of noise from one part of the building to another. At this stage, a full model has been built, but a review has not been undertaken in this respect.

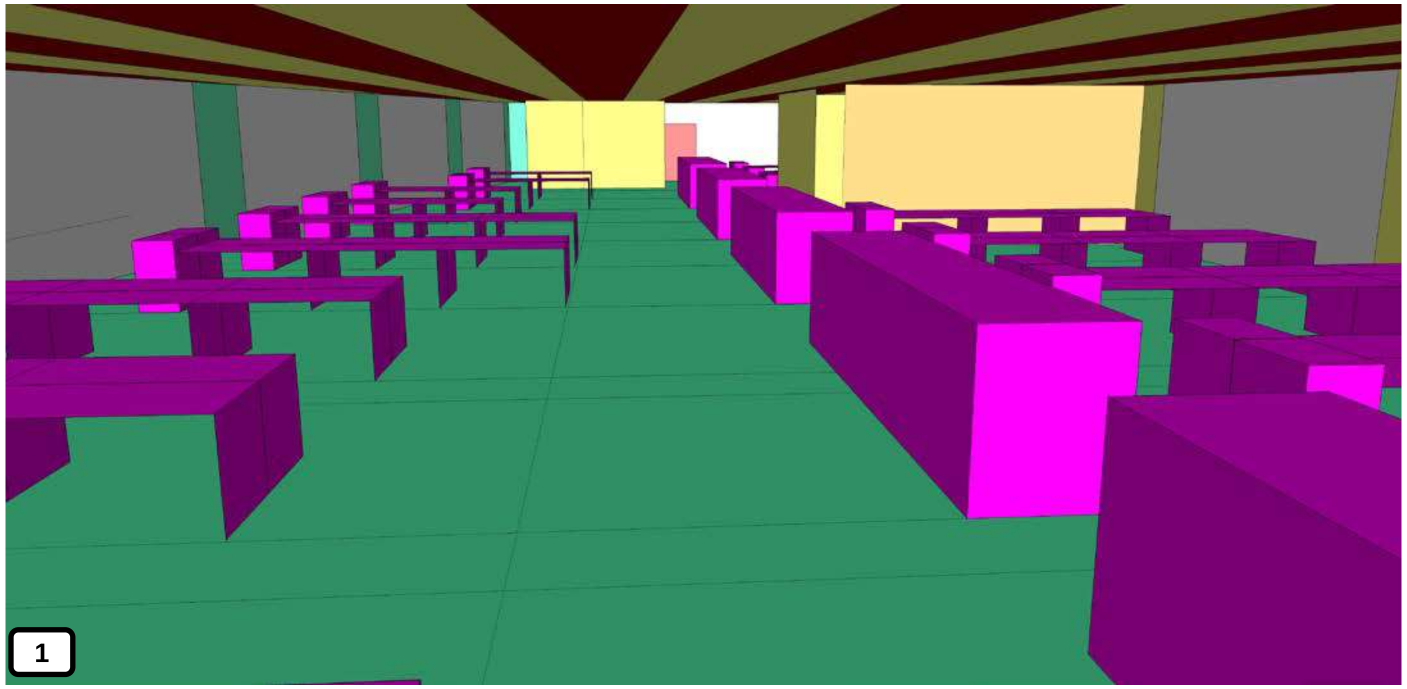
Please note, this type of modelling is limited since it does not include the effects of diffraction, hence small errors with the representation of the performance of acoustic screens may occur.

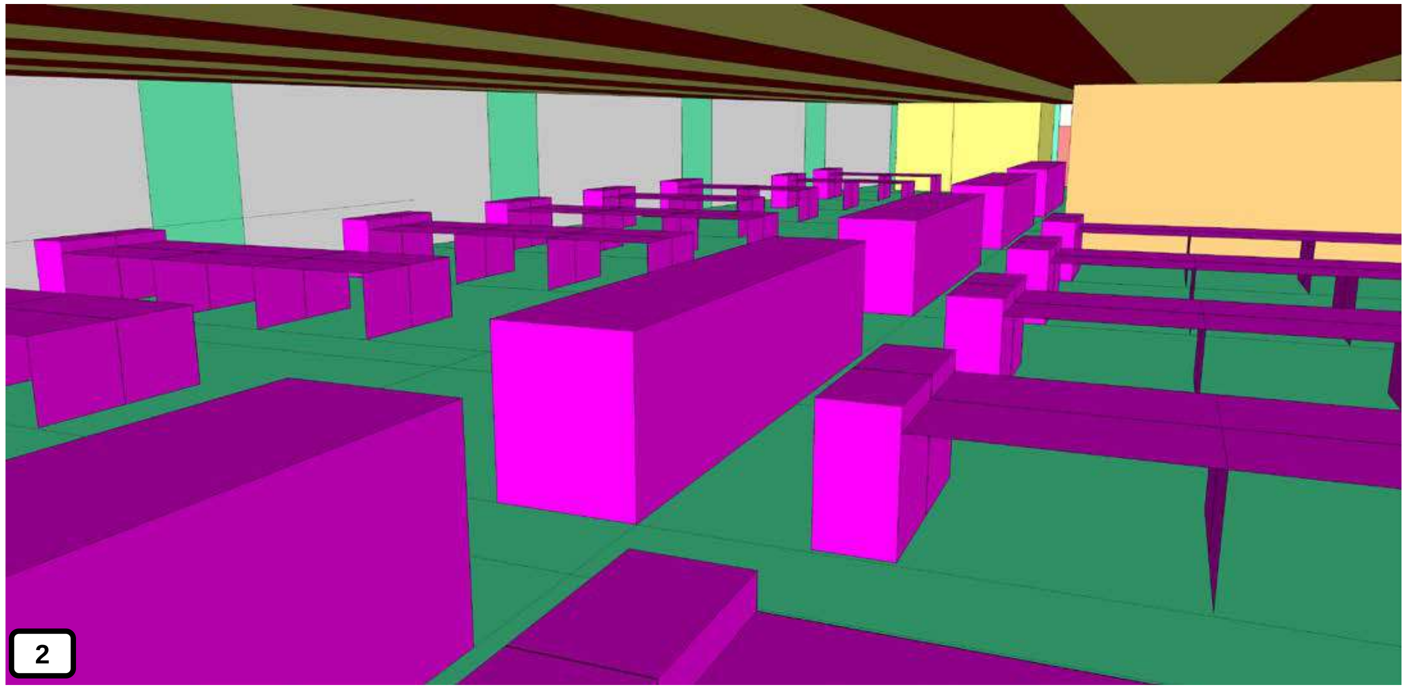
The second key advantage of this type of software is that it provides clear graphical differences. This allows the readers of these reports to easily understand and identify the difference between design options.

Calibration of Results

One of the core challenges when designing a low carbon building such as Keynsham Town Hall, is the fact that a concrete soffit with absorption is used. More traditional offices use suspended full acoustic ceilings to provide acoustic absorption within the office accommodation. Keynsham Town Hall as well as many other offices we have worked on do not.

MACH Acoustics has used our experience and test data from Allies and Morrison's office in London, Fingal and Kildare County Council offices in Ireland and Weston Super Mare council offices to calibrate the models used within this report.





Required Levels of Acoustic Performance

The acoustic requirement of a given space/building is dependent upon the function taking place in the space, as well as the tolerance of occupants in and around that space.

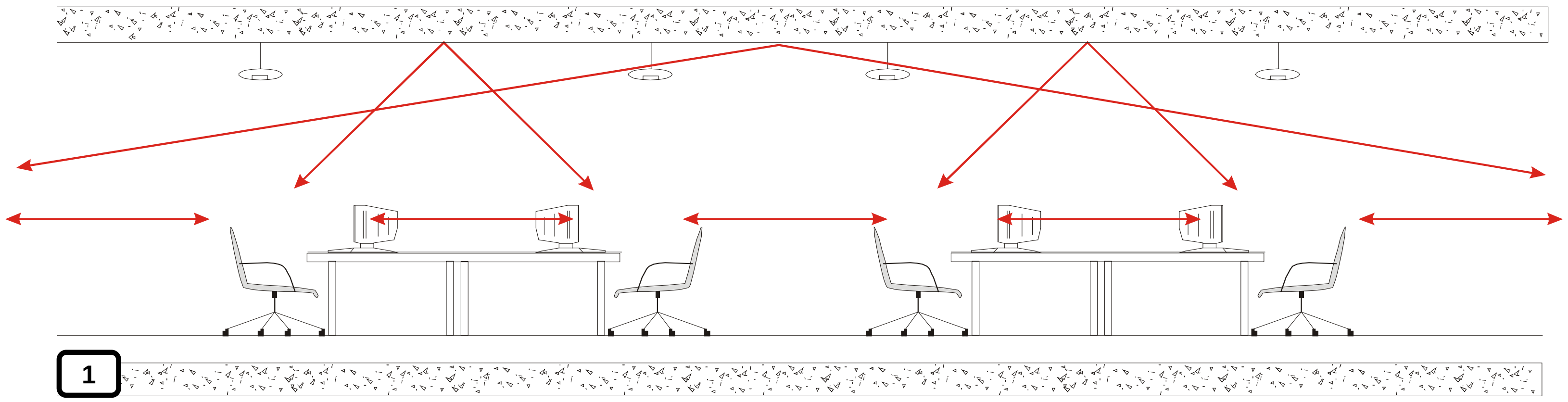
Individual activities will generate different levels of noise and will have different levels of tolerance to noise, depending upon the function taking place in the different office zones. This report is therefore seen as limited by the fact that the building as a whole and the function of the different parts of this building, have not been considered. This report focuses on the acoustics of open plan offices only. An assessment of the spread of sound through the Atrium is covered within a separate report to be issued shortly.

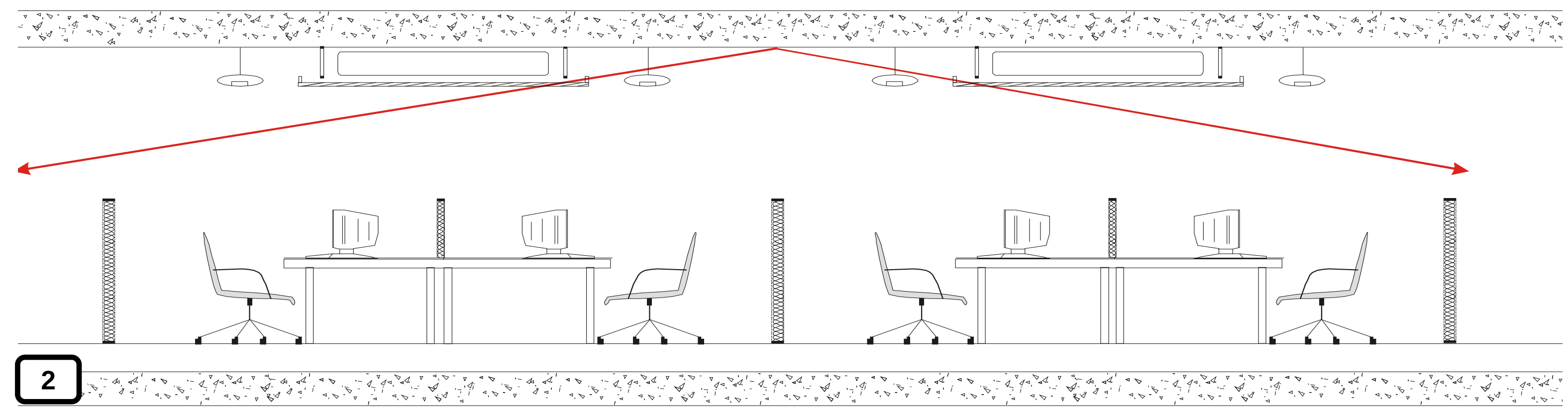
This report will not only look at typical absorptive treatments but also investigate the potential benefits of acoustic screens. This will be assessed by looking at the attenuation of sound over distance and the reduction in Articulation Index over distance as apposed to a single Reverberation Time limit.

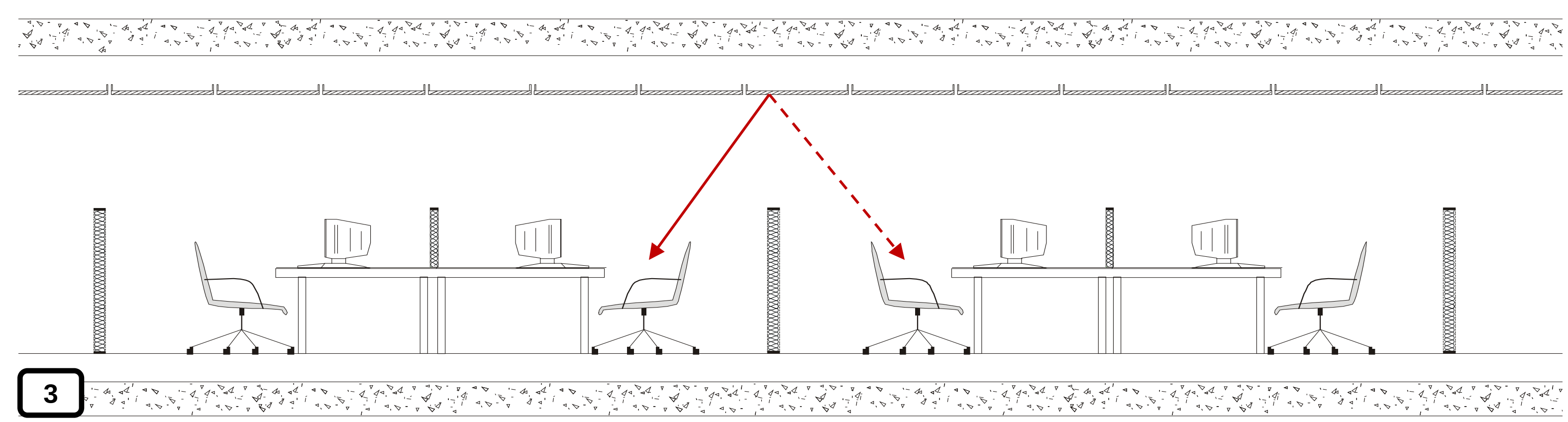
Screens without a doubt will increase the levels of separation between workstations, hence guidance documents will always lean towards recommending them. It is important to note that poor levels of privacy will potentially result in high levels of distraction/ disturbance, lack of focus and reduced productivity.

However, screens have a negative impact on the line of sight, communication and the general openness of an office, which is one of the key reasons for opting for this layout. One therefore needs to question the need for screens by understanding whether the right level of separation is being achieved between work stations without screens.

The images to the right provide design advice as to how best to maximise the separation between work stations, if this is seen to be desirable. In simple terms, the best way to do this is to break the line of sight by means of screens (2). To do this, the screens should be significantly higher than the noise source (mouth) and receiver (ear). It is therefore recommended that screens are no less than 1.5m height from the floor. The position of acoustic absorption in relation to the screen is also important. The optimum location is to place absorption on the ceiling (3) or wall adjacent to the screen, to reduce the degree of sound reflecting around it. Please see Appendix A for further information.







Room Acoustic Treatment

Room acoustics and reverberation times refer to the behaviour of sound within the room/space. Sound takes longer to decay in a reverberant room and thus has two consequences: firstly speech sounds become more difficult to hear as the long decay blurs successive syllables into each other. Secondly and <u>more importantly</u> in the case of an office building, a build-up of noise occurs as the sound takes longer to be absorbed. When this build-up of noise occurs, there can be a snowball effect as voices are raised to be heard above the noise (1).

An example of the snowball effect is often experienced in a café/ restaurant with tables seating 2, 4, 6 and 8 occupants. If the finishes within this space are hard, there will be little or no absorption of sound, which will result in a loud, harsh, stressful and unpleasant space. Additionally, it is difficult for people to talk in large groups as ones voice is masked by the background noise. This limits conversations to pairs and a maximum of 4 people around a table.

Positioning the same spaces outside prevents sound bouncing/ reflecting off walls (2), reducing noise levels around occupants. This reduction in noise promotes speech intelligibility, enabling all 8 members of a single table to hold the same conversation.

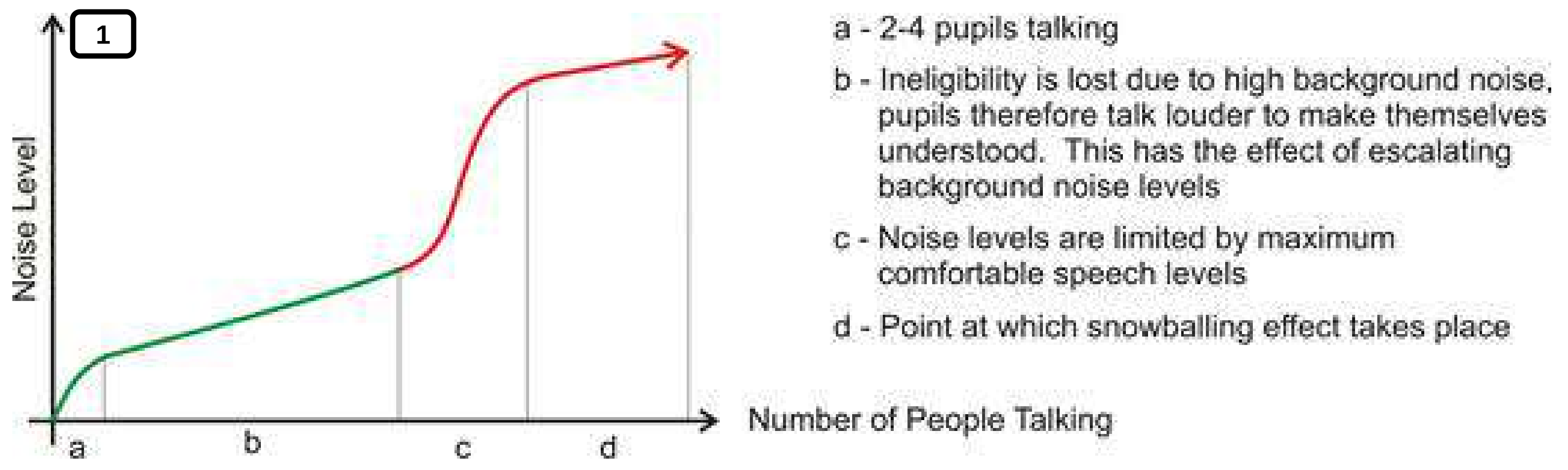
The café example is a little extreme but does demonstrate the importance of acoustic absorption in a space.

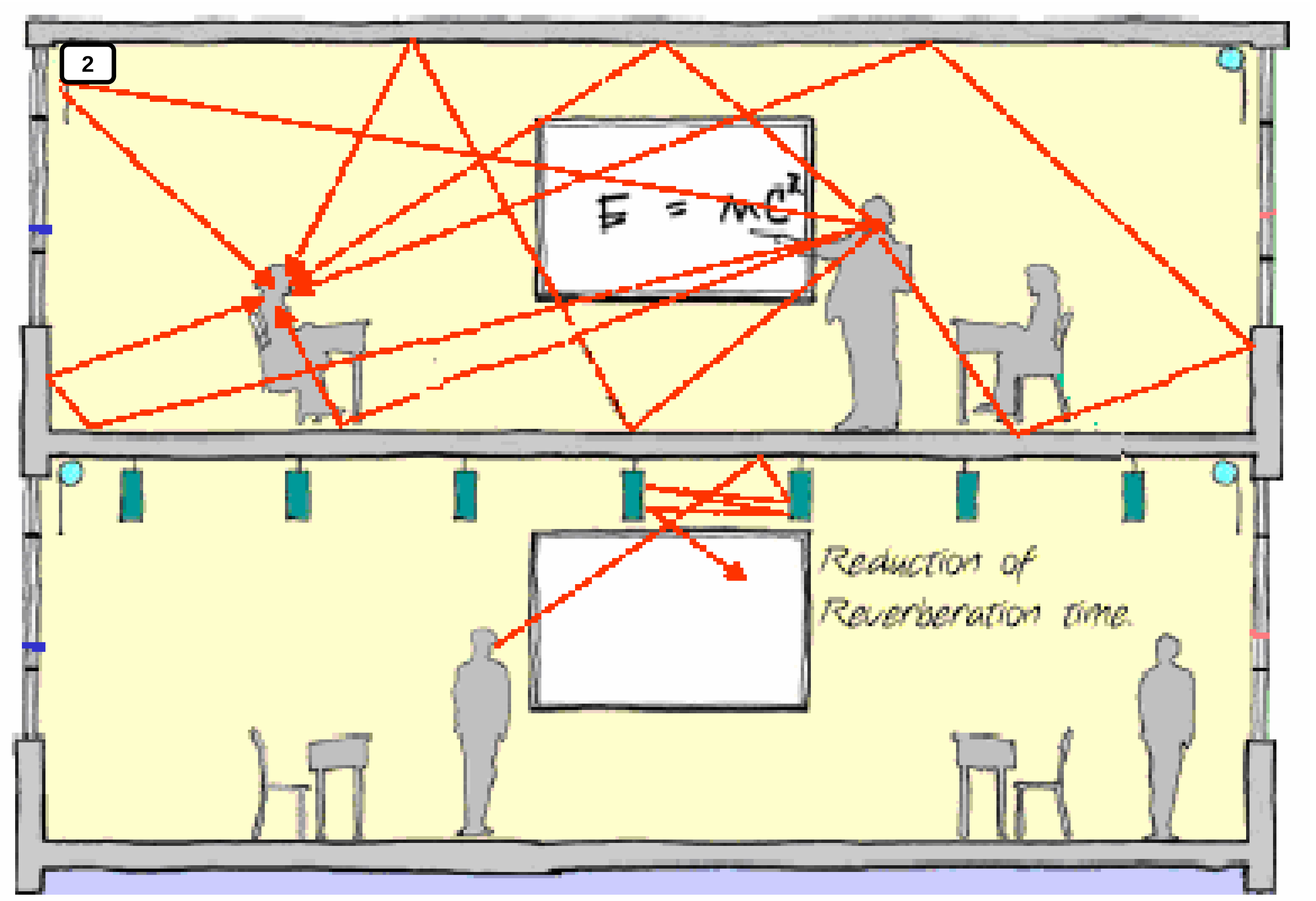
As a real reference of this effect, S. Airey has shown that occupancy noise levels are significantly reduced by controlling the snowball effect. This is achieved by increasing the levels of soft treatments in open plan spaces.

S. Airey's research shows that a **9 dB reduction** in occupancy noise can be achieved when **doubling** the levels of room acoustic treatments in a conventional classroom.

It must be noted that this research is based upon classroom environments, in MACH Acoustics experience offices tend to be quieter than classrooms and therefore the reduction in noise level due to suppressing the snowball effect is likely to be not as significant.

Reference is made back to the beginning page where investigation into an office with no treatment and hard reflective concrete walls and soffits presented no acoustic issues to its users.





Reviewing Proposed Room Acoustic Treatments

The image on the right (1) shows a plan view of an open-plan office located on the First Floor of the North building. The total floor area is approximately 710 m². The areas of the ceiling with absorbent treatment are marked up in yellow whereas those with concrete are shown in grey. The ratio of the total absorption area and the total ceiling area in the open-plan office is approximately 55%. All other open plan offices within this project offer a similar amount of acoustic absorption.

The proposed timber slated acoustic treatment proposed on the soffit is approximately 50% open area, on drawings, with 50mm mineral insulation. Calculations through the Zorba software predicted an absorption coefficient of 0.90, the open area must be no less than 30% open area for this absorption coefficient to be maintained.

The equivalent absorption area can be calculated as the product of the total area of acoustic treatment, times the absorption coefficient. If, on the other hand, the absorption coefficient is multiplied by the ratio of absorption area and total ceiling area, an equivalent 50% of the total ceiling area contributes to acoustic absorption within the space.

MACH Acoustics Design Advice

MACH Acoustics typically recommends a minimum of 35% of the floor area being acoustically treated in an open plan office environment.

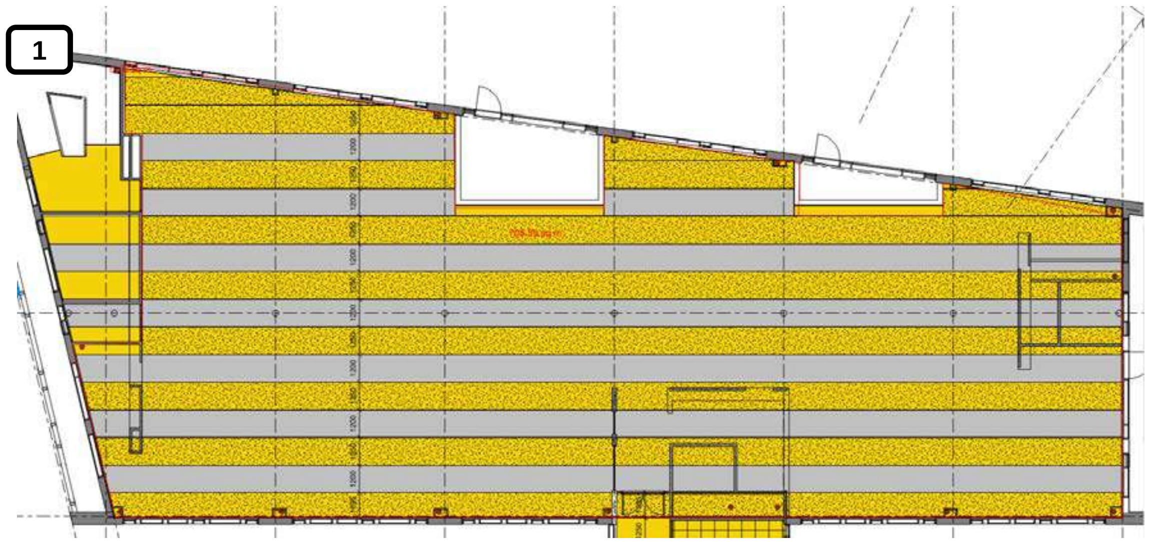
Therefore, according to the values presented above, this space should achieve the advised absorption based on the original proposed acoustic treatment.

Calculated Reverberation Time

Taking account of only a carpet floor finish and the proposed soffit treatment (1) and (3), the calculated reverberation time has been shown to be 1.1 seconds through modelling.

This value is below the reverberation time of 1.2 s as stated within the Employer's Requirements, and therefore the proposed level of treatment is suitable in that respect.

1



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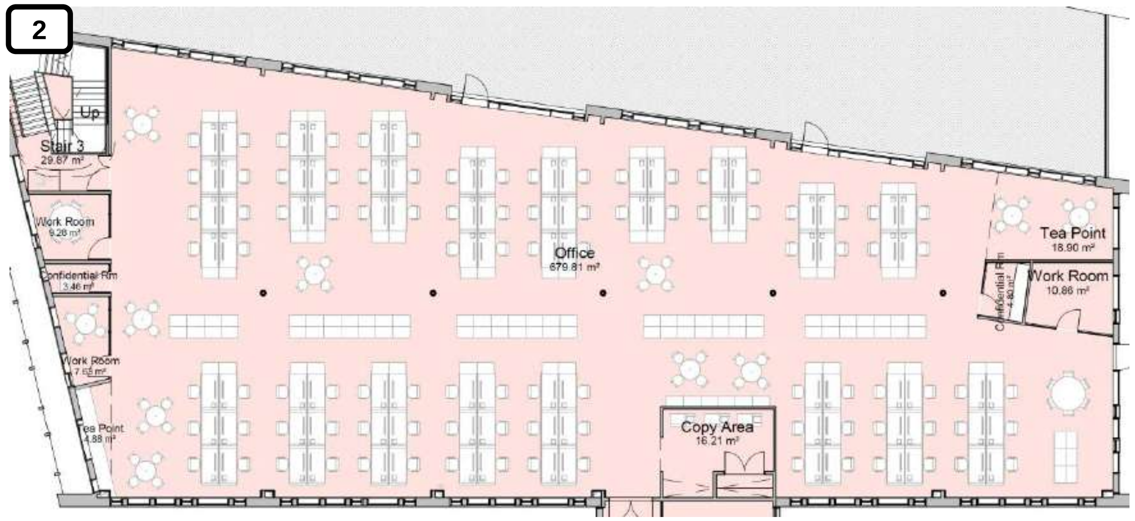

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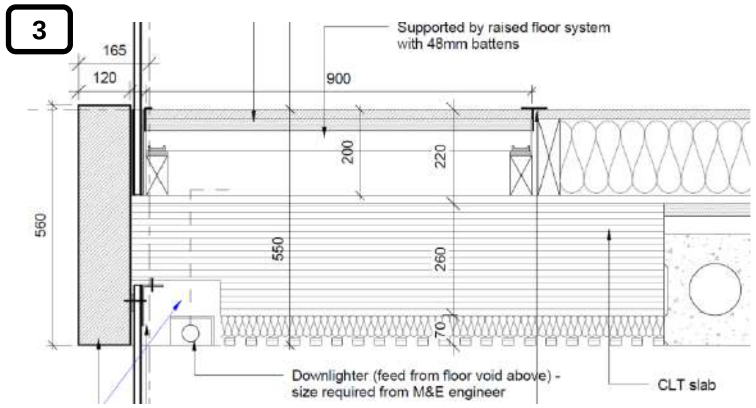


Acoustic Modelling - Introduction

The following pages of this report will now focus on the acoustic modelling which has been carried out. The modelling will first investigate the difference in performance for three scenarios, which are:

Reduced amounts of absorption: This scenario will look at reducing the acoustic performance of the proposed treatment by 50%. The model has done this by removing every other strip of absorption. However this would have a similar effect if the absorption became thinner, to provide an Absorption Coefficient = 0.45, where;
Total Absorption based upon the areas provided = 25% of soffit area.

Proposed amounts of absorption: This scenarios looks at the currently specified soffit.
Absorption Coefficient = 0.9, where;
Total Absorption based upon the areas provided = 50% of soffit area.

Increased amounts of absorption: This scenario looks at providing absorption to the whole soffit.
Total Absorption based upon the areas provided = 90% of soffit area.

These three scenarios have been chosen such to allow comparisons to be made between them. where it's aim is to inform the design team of the effects of these various treatments.

The modelling and calculations will mainly focus on Articulation Index (A.I.). This is a method to assess the intelligibility from a source to a receiver based upon background noise, reverberation time and attenuation over distance.

Using this tool to assess the open plan office, it is suggested that a quicker decay of speech intelligibility over distance indicates a reduced likelihood of noise disturbance from other distant work colleagues.

Following on from this first assessment, we will look at the potential introduction of the use of screens. It will be shown that screens can provide a significant performance increase over acoustic absorption alone. However it is understood this may not meet with the architectural language of the space, and therefore the information provided should be used to make an informed decision as to the acoustic design of the open plan office spaces

Effect of Room Acoustic Treatments

Three scenarios have been modelled of the 1st Floor North Block. All other open plan offices will provide similar results since their ratio of volume to absorptive area are similar. The three scenarios included the currently proposed soffit treatment, a reduced amount of soffit treatment and increased amounts of soffit treatment.

The scenario (1) has reduced the amount of treatment by approximately 50%. Based upon the soffit treatment achieving an absorption coefficient of 0.9, the percentage of soffit providing absolute absorption is 25%. This is also equivalent to reducing the absorption coefficient of the proposed layout to 0.45.

This has been calculated through the use of the Zorba software package, to be achieved by 25mm thick mineral wool behind timber slats with at least 30% open area.

Scenario (2) is the soffit as proposed, which discussed on the previous page provides a soffit with 50% absorption.

Scenario (3) investigates a full coverage of material, which provides the soffit with 90% absorption.

Results

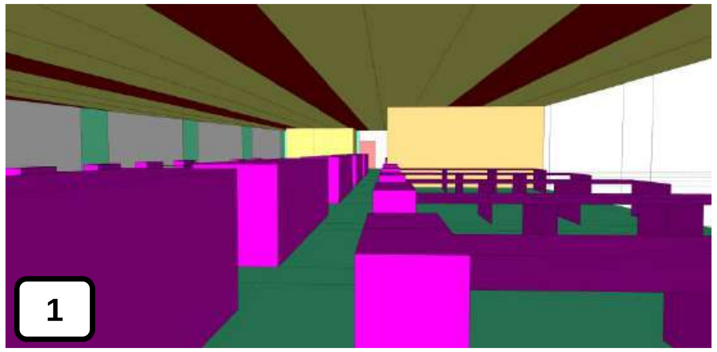
The results provided on this page show the sound pressure level across the room due to a single point source. This allows us to visually see the decay of sound. The results show there is approximately a 2 dB difference between each change in scenario, where a total difference between reduce levels of treatment to increased levels is 4 dB.

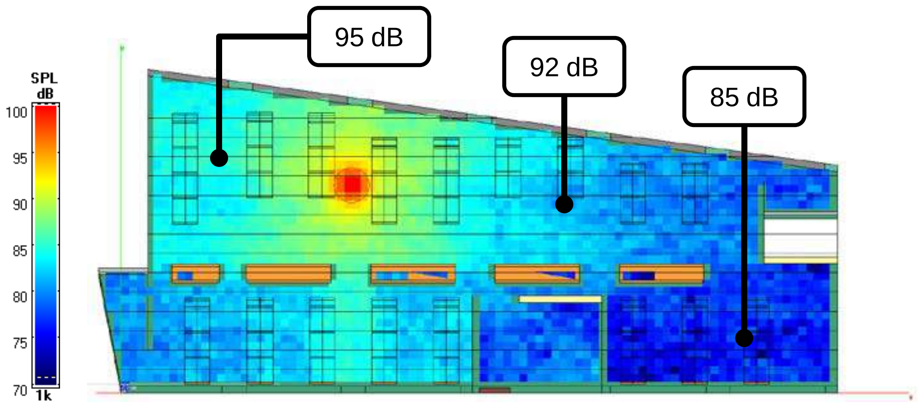
It is difficult to assess what these differences mean, except for the fact sound pressure level tends to reduce greater over distance when there is more treatment on the soffit.

To have these results provide more understanding, they will be used within a calculation to show the change in articulation index over distance which is provided on the following page.

The average reverberation times between 125 Hz to 8kHz (T_{20}), calculated through modelling shows the proposed soffit treatment achieves the ER’s. There is little variation between the scenarios due to the space being so large with treatment only located on the soffit and floor (carpet). This suggests an assessment of attenuation / articulation index over distance may be more appropriate.

Reduced Amounts of Treatment – Equivalent to 25% total absorption

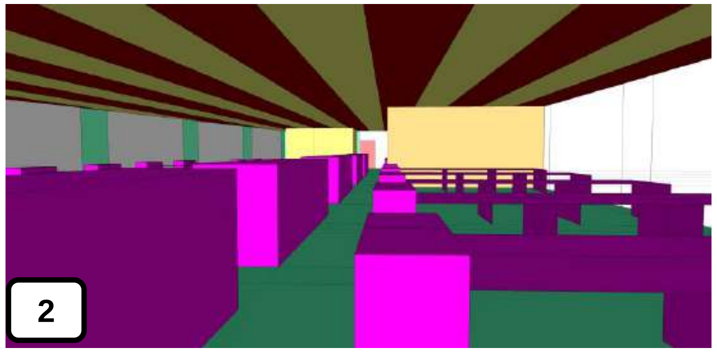


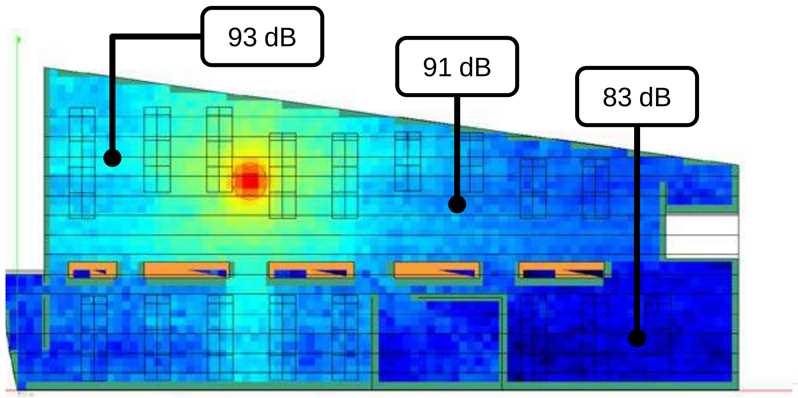


Reduced acoustic treatment

RT= 1.3 seconds

Proposed

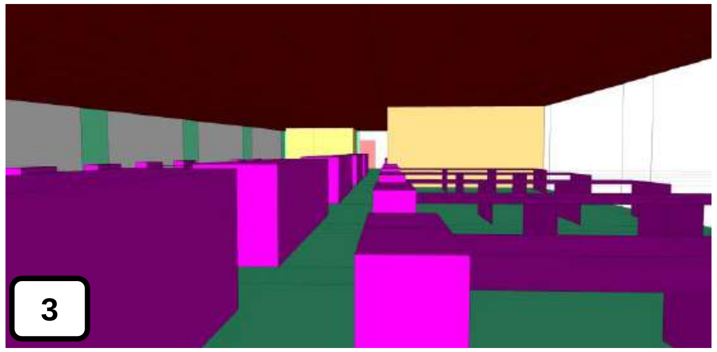


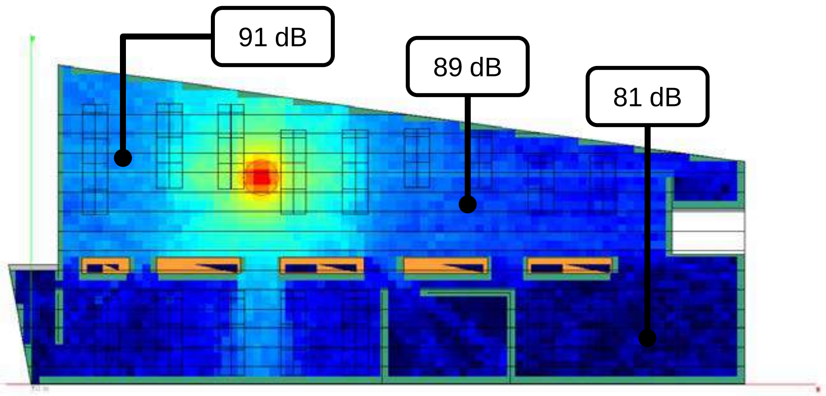


As designed – no additional treatment

RT= 1.1 seconds

Increased





Increase acoustic treatment

RT= 1.0 seconds

Articulation Index

Articulation Index is a similar, alternative measure of STI (Speech Transition Index). The advantage of Articulation Index is that it can be calculated using a spreadsheet based upon the results of the noise decay modelling. This means that graphs and other analytical tools can be calculated with greater ease. The table below provides a subjective interpretation of Articulation Index (AI).

AI Value	Subjective Interpretation
0 – 0.3	Marginal Intelligibility
0.3 – 0.5	Poor Intelligibility
0.5 – 0.7	Good Intelligibility
0.7 – 1	Very Good Intelligibility

The purpose of looking at the AI allows us to see which scenario has the fastest reduction of AI with respect to distance. Where the AI reduces quickly this suggests that occupants will become less interrupted by co-workers sat at a distance.

Results

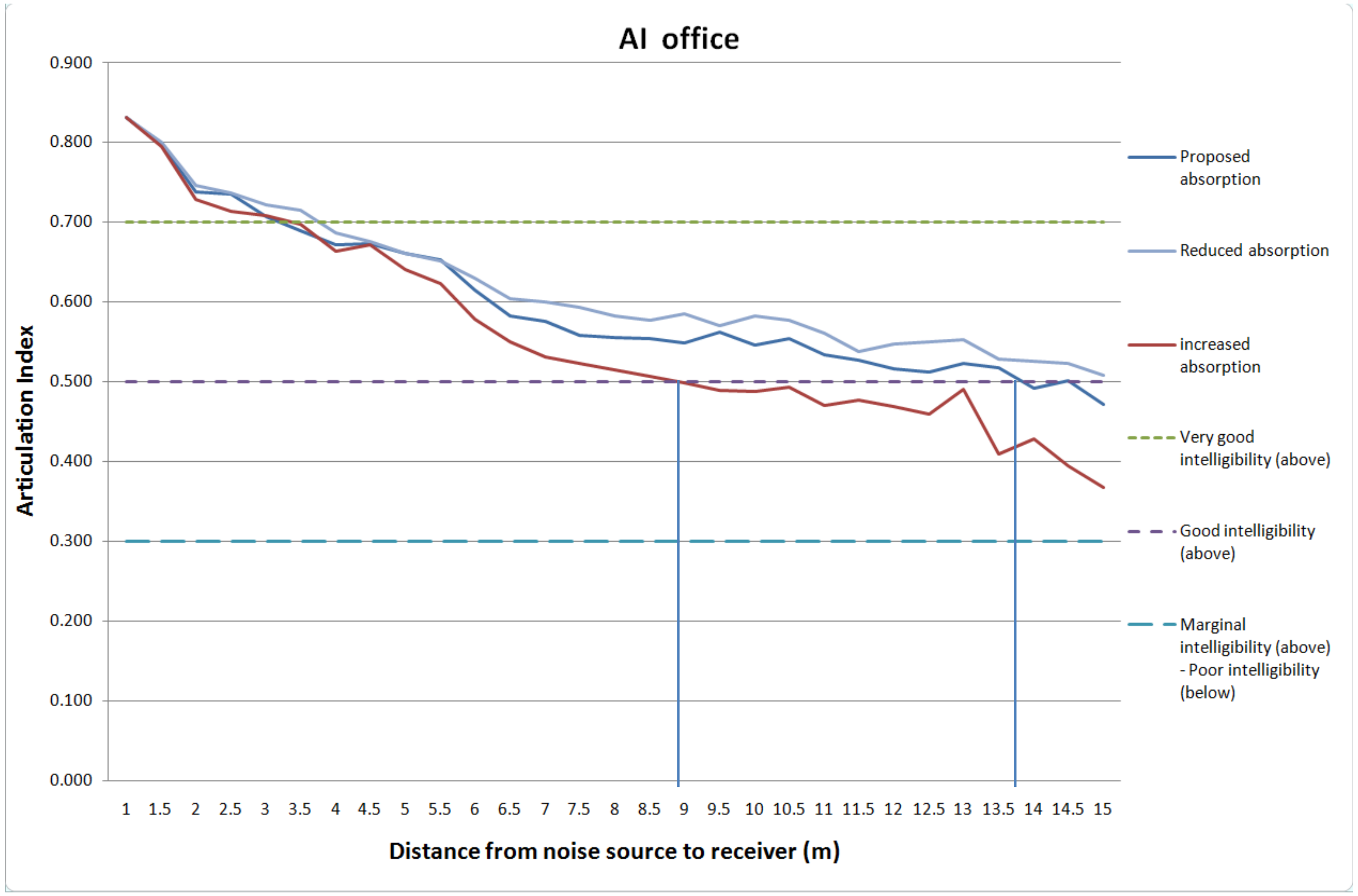
The key observation taken from this graph is that the small difference in sound decay over distance, shows a moderate change to speech intelligibility levels over distance.

Three key points are taken from the graph on the right.

All three scenarios have “Very Good” levels of intelligibility up to 3.5 meters from the source, and show little difference between them up to 5 meters.

There is a noticeable reduction in AI levels as a function of increased levels of room acoustic treatments.

The increased level of treatment reaches a “poor level” of intelligibility at 9 meters, whereas the proposed amounts of treatment reach this at 14meters.



Screens Between Work Stations

Two models have been built to assess the impact of acoustic screens on the spread of sound within the offices. The two models have looked at introducing screens for the proposed treatment scenario, and the reduced treatment scenario. These models will be compared against the results previously shown for the increased treatment option with no screens.

The first scenario presented below (1) is the increased treatment with no screens, which has already been discussed and will be used for comparisons only.

The second scenario (2) has modelled the office space with the currently proposed levels of acoustic treatment with the addition of screens, shown by the red objects in the image.

The third model (3) is the reduced treatment with screens.

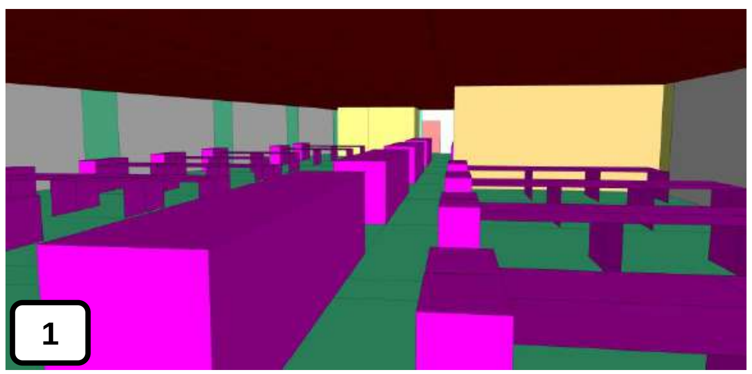
Results

The results below are more dramatic than simply placing enhanced levels of soft treatments within the office. This is because the line of sight between work stations is broken.

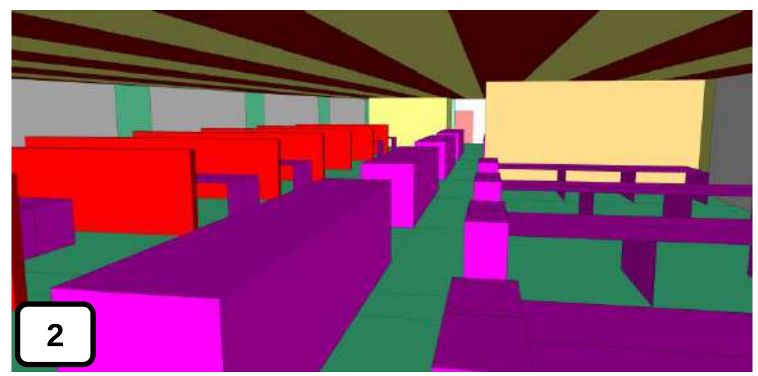
The modelled results below clearly show the benefit of the including acoustic screens. This is because reflections off the soffit are being controlled.

In MACH Acoustics view, the most important aspect to take from these results is that sound from a given noise source is more contained when screens are used. This is because the most influencing factor on speech travel in the office in front of the speaker, is the direct path. Breaking the direct path therefore has a greater improvement than other additional forms of room acoustic treatments. This has been explained in more detail within Appendix B and C.

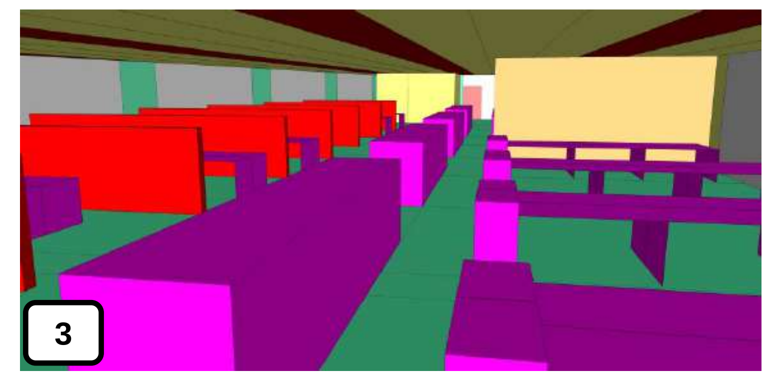
Increased Treatment – No Screens

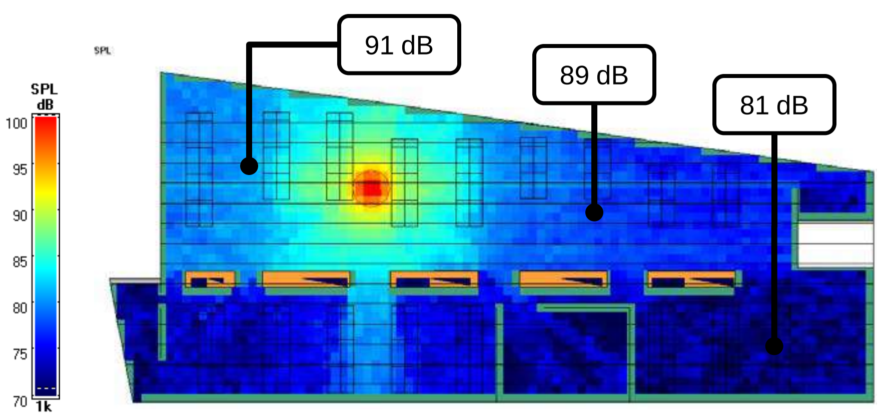


Currently proposed treatment with screens

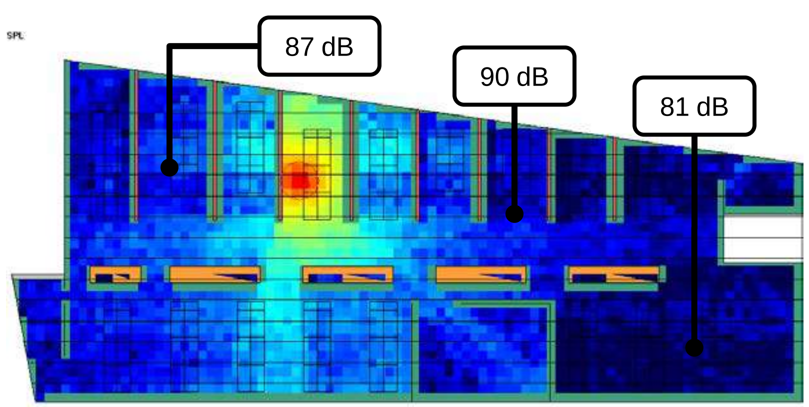


Reduced treatment with screens

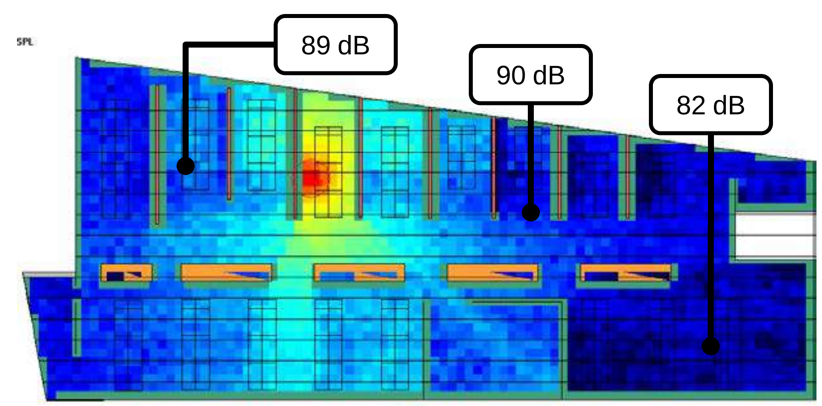




RT= 1.0 seconds



RT= 1.1 seconds



RT= 1.3 seconds

Calculated AI Levels – Across Screens

As in the case of room acoustic treatments, an Articulation Index assessment has been undertaken over distance through the office, including the effects of screens.

The graph on the right shows AI levels for the office with increased amounts of absorption with no screens, as shown in the previous assessment.

The articulation index is also included for the proposed levels of acoustic treatment with the inclusion of screens between desks. The AI has also been calculated for reduced treatment including screens.

Results

The graph to the right clearly shows the beneficial effects of screens, indicating a dramatic drop in speech intelligibility on the far side of the screen.

These results also show that the screens will improve the acoustics of the office space, even under the current levels of proposed acoustic treatment.

It has also been shown that there is an improvement in the performance for when reduced levels of acoustic treatment are used in combination of screens. This improvement indicates a similar to or better reduction of articulation index over distance when compared to the increased absorption scenario with no screens.

Therefore, if the absorption on the soffit were reduced, and it was felt necessary, acoustic screens could be introduced to increase the rate of decay of articulation index. This has been indicated by the acoustic modelling to be better than the current proposals and similar if not better than the increased absorption scenario with no screens.

AI Value	Subjective Interpretation
0 – 0.3	Marginal Intelligibility
0.3 – 0.5	Poor Intelligibility
0.5 – 0.7	Good Intelligibility
0.7 – 1	Very Good Intelligibility

Conclusion

As mentioned previously, this report has not set out to dictate how much acoustic absorption is required within the open plan office space but to look at different design strategies to allow for an informed choice to be made.

An employer's requirement has been set within the tender documentation of 1.2 seconds. It has been shown through modelling that the currently proposed soffit treatment should achieve T_{20} = 1.1 to 1.2 seconds and would therefore meet this criteria.

We would also need to highlight that the Allies and Morrison Office's Case Study, discussed at the beginning of this report, show's that the occupants of a hard reflective, concrete office can be fully satisfied with the acoustic performance of such a space.

This report has suggested that revelation time is not the only design method available when designing open plan spaces. Attenuation over distance and rate of decay of the articulation index may be used as other design tools.

Using these methods we have shown how increased and decreased levels of acoustic absorption has an effect on these parameters.

However it has been shown that the greatest improvements are typically gained with acoustic screens, since these reduce the dominant direct sound path.

There are a number of results presented within the report. Overall it is seen that the two sets of Articulation Index assessments provide the clearest results, Pages 6 and 8.

The first observation is that there is a clear increase in the decay of sound over distance as absorption increases. This has positive correlation to the decay in articulation index with distance.

This is considered a useful method since a faster decay rate over distance, may indicate disturbances from co-workers from other locations in the office would be reduced.

The second observation is that the use of screens provide a greater improvement to the rate of decay of AI over acoustic absorption alone. It has been shown that including screens with a reduced amount of absorption on the soffit, such to provide total equivalent absorption area of 25%, is equal to if not better than if the entire soffit were treated with absorption.

This is not to say that if the acoustic performance of the soffit were reduced, acoustic screens are required. Especially since Mach Acoustics has had experience where occupants of open plan offices have been satisfied with the acoustics where no treatment has been provided.

Summary

In summary, the proposed levels of acoustic treatment on the soffit could be considered sufficient and have been shown to meet the ER requirement of 1.2 seconds for a furnished but not occupied room. When occupied with books, paper chairs etc. The reverberation time may reduce further.

Reducing the treatment as specified in the report ,will produce reverberation times slightly higher, T_{20} = 1.3s, when un occupied.

Reducing the performance of the soffit may produce an acceptable working environment. If screens where to be included in combination with the reduced treatment, this would provide a similar if not better environment than if the entire soffit were covered in absorption and screens where not used between desks.

Appendix A – 3rd Floor Office

The third floor open plan office spaces are very similar to the lower floors with the exception that the floor to ceiling height s are greater and the soffit is angled and not flat.

A second model has been created of the 3rd floor North Block in order to assess this variation in volume to absorptive treatment ratio.

The calculated average RT from 125 Hz to 8kHz, with the proposed amount of soffit treatment is T_{20} = 1.2 seconds. This is only 0.1s greater that the offices on the lower floors and meets the ER's. This small variation is possibly the cause of the angled soffit creating a more diffuse sound field which can have a positive effect when treatment is located on one surface only, i.e. soffit.

The graph to the right plots the calculated AI for the third and first floor offices with the proposed treatment. Here it is shown that the AI is very similar for each floor and that no really change is experienced, which would be contributed to the reverberation time remaining approximately equal.

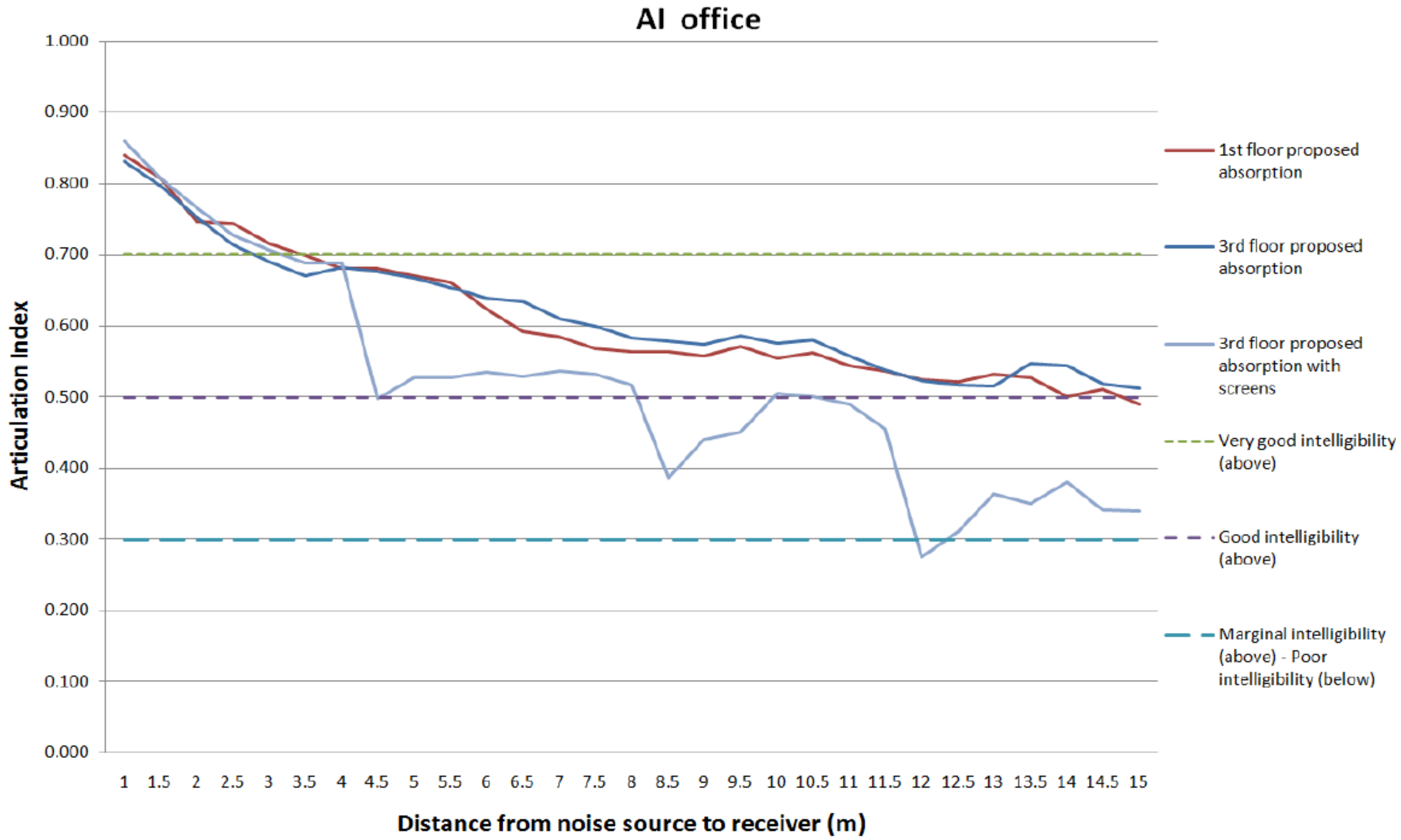
The light blue line in the graph indicates the drop in AI with the use of screens. As seen in the other AI assessments the use of screens show a dramatic reduction of intelligibility over distance, which is due to inhibiting the direct sound path.

Summary of Third Floor

It has been shown that the reverberation time T_{20} will be in the region of 1.2 seconds which is the ER set for this project.

There is little difference in the AI rate of decay over distance when comparing the two floors. Despite the volumes being different from each other this similarity is likely due to the more complicated room geometry providing a similar reverberation time.

AI Value	Subjective Interpretation
0 – 0.3	Marginal Intelligibility
0.3 – 0.5	Poor Intelligibility
0.5 – 0.7	Good Intelligibility
0.7 – 1	Very Good Intelligibility



Appendix B – Maximising the performance of Acoustic Screens

The purpose of this appendix is to explain the key factors affecting the performance of screens. This information is therefore aimed at ensuring that the maximum benefit from screens is achieved if these units are chosen to be used within this development.

Screen size, height and position (Cases 1 – 2 – 3):

The performance of a screen is dependant upon the distance the sound has to travel over the screen, therefore the higher the screen the better the performance. The minimum requirement for the screen is to break the line of sight between the source and receiver. As a minimum, the screen height should be no lower than head height, to prevent the spoken voice from passing over the screen (see Cases 1, 2 and 3).

Positioning of screens (Cases 4 and 5):

The acoustic performance of an acoustic screen is always limited by the fact that sound can pass over or around a screen. It is generally accepted that a well positioned, appropriately sized screen can provide up to 15 dB(A) of sound reduction, when located in a free field condition i.e. outside in an open field.

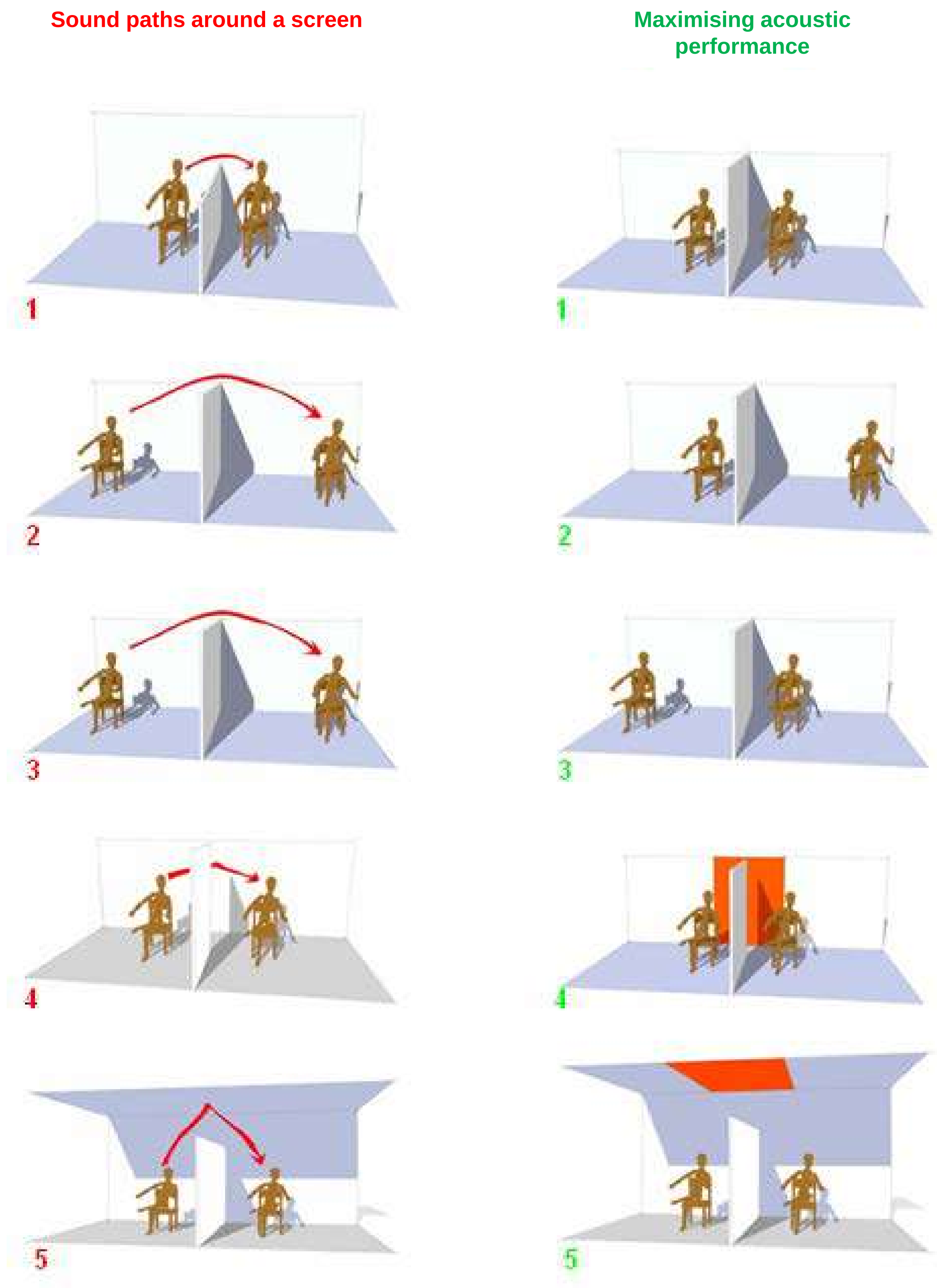
By bringing a screen indoors, reflections off hard surfaces are likely to compromise the screen further. Here, the maximum performance of a screen is likely to be limited to 10 dB(A).

Cases 4 and 5 show the effect of placing a screen adjacent to a hard surface. Such to ensure the integrity of the screen in Case 1, the screen must be placed adjacent to a hard surface i.e. a wall, table or other hard object and sealed with mastic. There should also be no air gaps between the screen and any other surfaces. The alternative to Case 2 is to place an absorbent surface along the length of the reflective area.

Materials:

As sound can pass over the top and around the screen, screens are also often compromised by reflection. There is therefore little benefit in provide high levels of acoustic separation through the screen itself. The only acoustic requirement for the screen is therefore to have a mass equal to or greater than 10kg/m^2.

Ideally, the screen would be finished with an absorbent covering, i.e. mineral wool covered with cloth. This requirement is only likely to slightly increase the performance of the screen. On the other hand, finishing the screen with a soft covering will prevent the passage of sound as a result of reflections.



Appendix B – Screen Types – A

Screens are often disregarded during the design stage of a building due to the fact that the appearance of green, canvas covered, floppy structures forming cellular enclosures around the office accommodation, is not desirable.

In MACH Acoustics view, it is naive not to have some degree of separation between different working zones within the office accommodation.

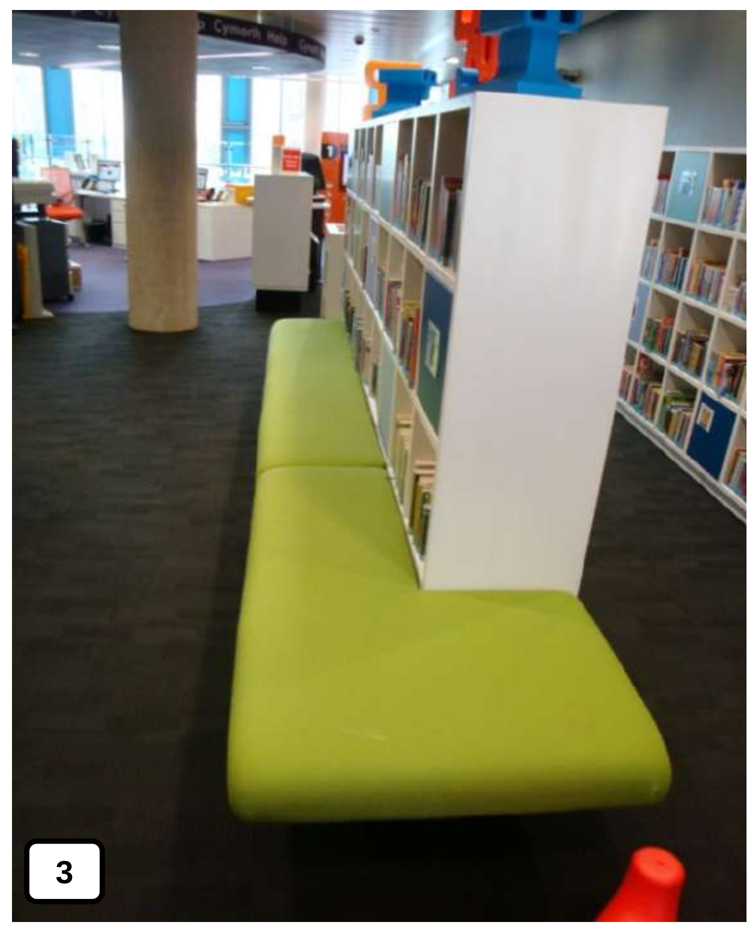
This Appendix therefore aims to provide an illustration of a range of screens types with very different appearances.

Images 1 and 2 show how shelves have been used to provide exceptionally effective screens. These images show how the line of sight between two working zones can be broken without the introduction of what looks to be an acoustic screen.

Images 3 and 4 demonstrate a more creative type of screen. From here, it is clear that a range of different screen types can be combined with seating to form an acoustics break within an open plan environment. These seats could therefore be used to form a break out zone between work stations.


1


2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Appendix B – Screen Types – B

Round screens are an interesting method of providing break out zones within an office environment. The advantage of round screens is an increased level of acoustic screening, as the sound source tends to be more enclosed within this type of environment.

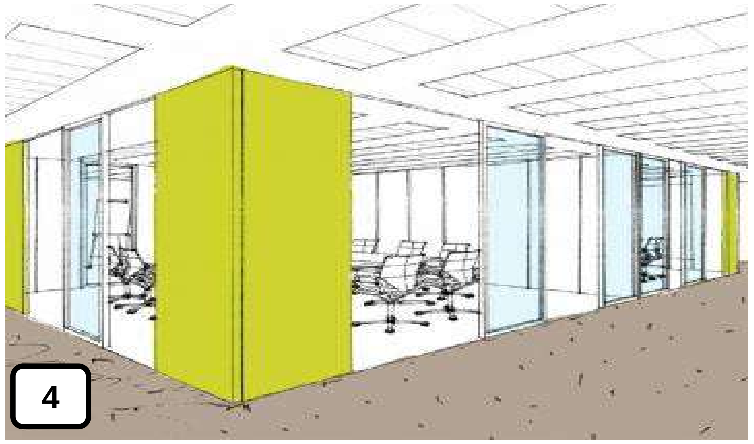
A second advantage of the screen shown in image 1 is that two different working zones can be placed on either side of this arrangement. The structure will not only increase the distance between the two different working zones, but will also effectively provide high levels of acoustic screening between these two areas.

Flexibility in an office is an important aspect of these designs. Images 3 and 4 show an interesting concept used to provide flexible screening within an office space. Here, the head track to moveable walls has been installed into a range of locations. Light weight, low performance moveable wall panels can then be moved around the office accommodation, allowing for flexible screens to be moved as the function of the office accommodation changes over time. Please note that there are many different alternatives to this arrangement.


1


2


3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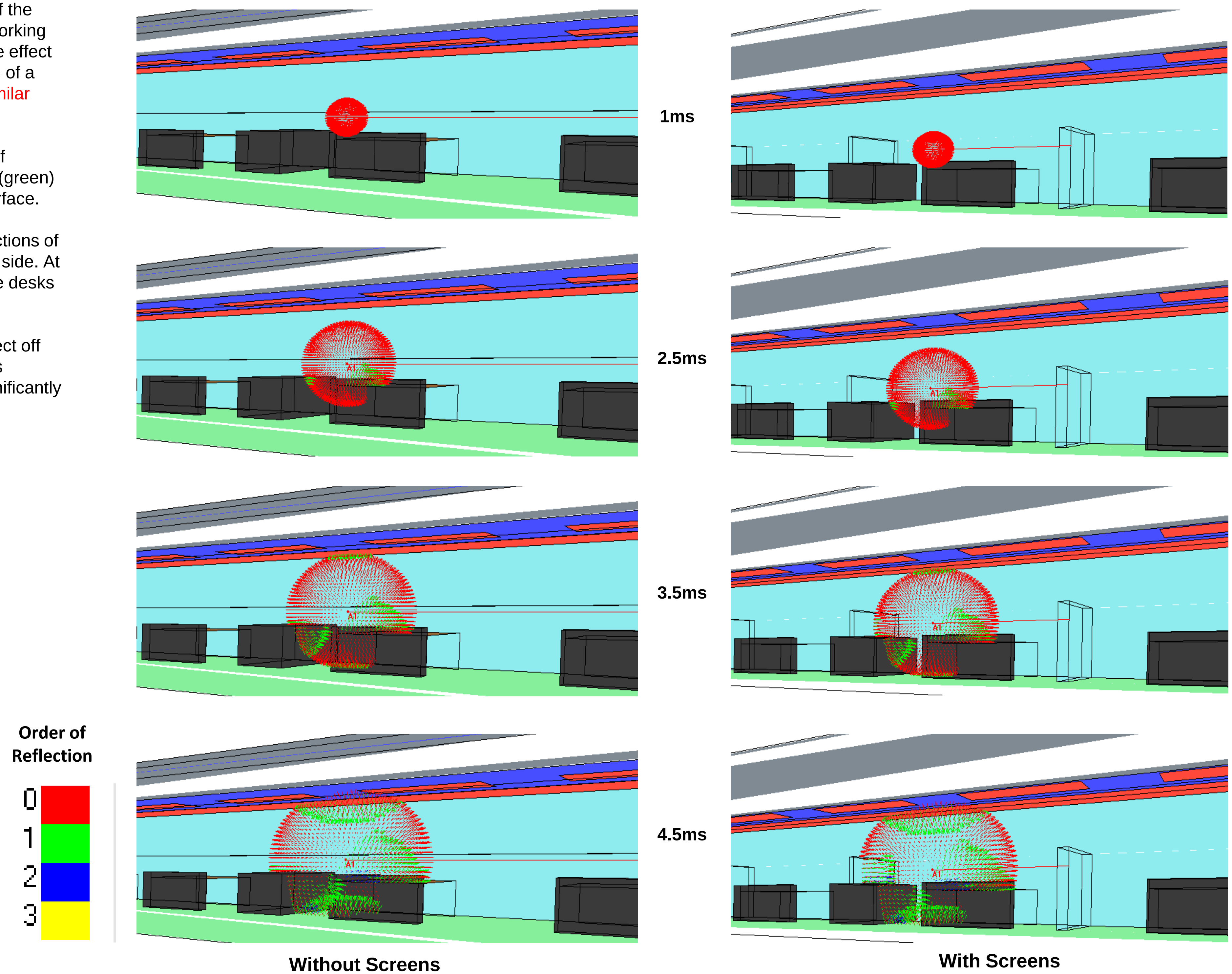
Appendix C – Time Frame Analysis of Wave Fronts

This section of the appendix provides visuals of the way in which sound rays propagate between working bays. These visuals are useful in examining the effect of reducing direct sound between desks by use of a screen. Please note they are based upon a similar building to Kyensham Town Hall.

Sound rays are represented in terms of order of reflection, i.e. 0 (red) being direct sound and 1 (green) being sound that has been reflected off one surface.

The images on this page show very early reflections of sound before it has reached the screens either side. At 2.5ms the first reflections can be seen off of the desks and shelves around the speaker.

At 3.5ms and 4.5ms sound can be seen to reflect off the panel/ceiling above the desks. This panel is absorptive and hence these reflections are significantly weaker than the direct sound that hit it.



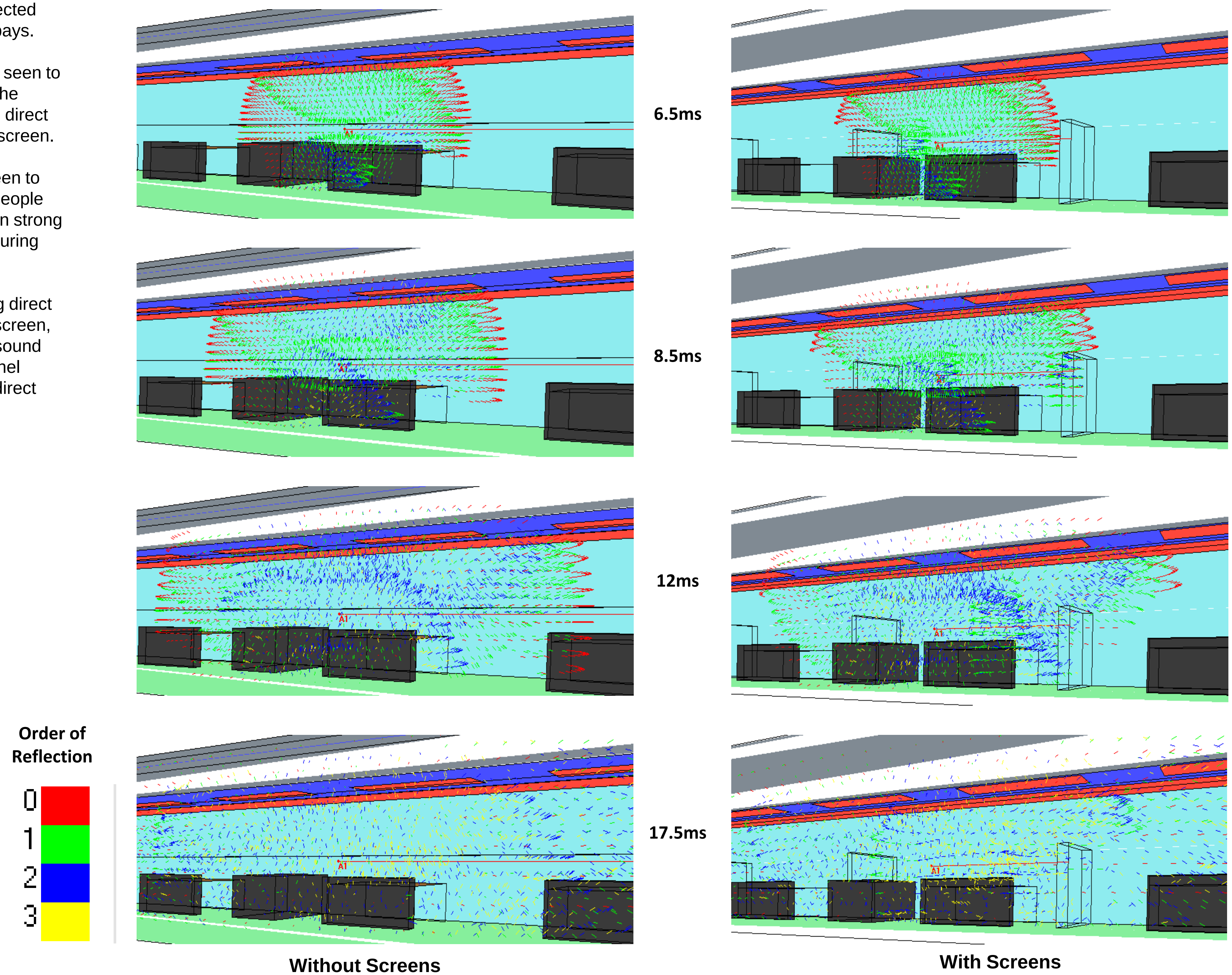
Appendix C – Time Frame Analysis of Wave Fronts

The images on this page shows direct and reflected sound reaching the screens between working bays.

At 8.5ms direct and 1st order reflections can be seen to reflect back off of the screen and back toward the speaker (blue sound rays). It is seen that some direct and reflected sound travels over the top of the screen.

However the direct sound over the screen is seen to also travel over and above the head height of people sat at the next table (12 ms). Without the screen strong direct sound can be seen reaching the neighbouring table.

This clearly demonstrates the effect of reducing direct sound via use of an acoustic screen. With the screen, reflected sound at the next table is seen to be sound that has been reflected off of the absorptive panel above, and hence is significantly weaker than direct sound.



Appendix C – Time Frame Analysis of Wave Fronts