Development of a two-step algorithmic method for layout assessments in the auditory domain

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Abstract

Creating a workspace layout for effective collaboration is important for critical Command and Control (C2) spaces. Computational models have been proposed to address this requirement, offering a mathematical method to analyze the effectiveness of communication within such collaborative environments. With an objective to improve an existing DRDC layout modeling tool, LOCATE, this study was performed to investigate the use of speech intelligibility indices for measuring communication effectiveness, as well as two other factors (auditory distraction and speech privacy) that influence users' satisfaction with their workspace. Based on a literature survey, the speech interference level was identified as a preferable metric for intelligibility measure and a two-step algorithmic method was proposed to analyse layout effectiveness based on the perspectives of both speakers and listeners. Three sample models were presented in this report to describe the computational procedure for the proposed method. Future incorporation of this method into a software tool will enhance DRDC's capability in workspace layout modelling.

Significance to defence and security

The study was conducted to support DRDC's project 01ab which is entitled the Royal Canadian Navy (RCN) crewing and human factors, specifically its Work Breakdown Element to develop a workspace layout modeling tool for analyzing critical control spaces on future RCN platforms. The proposed algorithmic solution reflects a major expansion of DRDC's layout modeling capability by introducing layout metrics that have not been considered in existing methods such as LOCATE. Incorporation of the proposed algorithm into future modeling software will allow a more comprehensive assessment of operator requirements in C2 space layouts.

Résumé

Il importe d'aménager un espace de travail favorisant une collaboration efficace dans les postes névralgiques de commandement et contrôle (C2). Les modèles informatiques proposés pour répondre à ce besoin offrent une méthode mathématique pour analyser l'efficacité des communications dans de tels environnements de collaboration. Dans le but d'améliorer LOCATE, un outil de modélisation de l'aménagement utilisé actuellement par RDDC, la présente étude explore le recours à des indicateurs d'intelligibilité de la parole afin de mesurer l'efficacité des communications, ainsi que deux autres facteurs (distraction auditive et confidentialité des entretiens) qui ont une incidence sur la satisfaction que tire l'utilisateur de son espace de travail. La revue de littérature révèle que le niveau d'interférence avec la parole est la mesure privilégiée de l'intelligibilité, et une méthode algorithmique en deux étapes est proposée pour analyser l'efficacité de l'aménagement du point de vue du locuteur et de l'auditeur. Trois exemples de modèles sont décrits dans le présent rapport pour énoncer la procédure de calcul sur laquelle repose la méthode proposée. L'intégration de cette méthode à un outil logiciel permettra d'accroître la capacité de RDDC en matière de modélisation de l'aménagement de l'espace de travail.

Importance pour la défense et la sécurité

L'étude a été réalisée à l'appui du projet 01ab de RDDC portant sur le recrutement et les facteurs humains de la Marine royale canadienne (MRC), et s'intéresse en particulier à l'élément de répartition du travail afin de mettre au point un outil de modélisation de l'aménagement de l'espace de travail qui pourra servir à l'aménagement des postes de contrôle névralgiques des futures plateformes de la MRC. La méthode algorithmique proposée ouvre la voie à une expansion importante de la capacité de modélisation de l'aménagement de RDDC en faisant intervenir des mesures de l'aménagement dont ne tiennent pas compte les outils existants tels que LOCATE. L'intégration de l'algorithme proposé à un futur logiciel de modélisation permettra de réaliser une analyse plus exhaustive des besoins des opérateurs dans les postes de C2.

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1 Introduction

The spatial layout of Command and Control (C2) spaces, such as a command centre or an operations room, is generally an important design requirement for many Canadian Armed Forces operations [1]. Effective layout configurations are particularly important for control spaces on a naval platform due to the high cost associated with design modification at a later stage of platform construction. A modelling solution has been proposed for the Defence Research and Development Canada (DRDC)'s Royal Canadian Navy (RCN) crewing and human factors project, to develop a software tool for generating digital models of workspace and assessing layout effectiveness using algorithmic methods. This report documents the development of a 2-step algorithmic method to evaluate layout effectiveness by considering operator work requirements in the auditory domain.

1.1 An existing tool and its limitations

The idea of a modeling tool for designing and evaluating workspace layout is not new. A software tool called LOCATE was developed by DRDC for this exact purpose. LOCATE was constructed to address *room layout* designs, where "the geometrical scale of the workspace is within the intermediate to far range of human sensory performance [2]", and therefore human perceptual limitations become a critical factor that drives layout design. In contrast, this factor is commonly not a key consideration for the design of either *workstation layout* or *building layout* since the size of workspace in these two cases is either completely within or beyond the limit of human sensory capabilities. To evaluate a room layout in LOCATE, an analyst needs to model information transmission patterns within the workspace by using communication links to indicate the source and receiver of all information transmission paths. The effectiveness of each link is then modelled using a mathematical link strength function (LSF) which is sensitive to either the length or direction of a link vector. After the position and orientation of each operator (and her workstation) is determined in a solution, LOCATE can compute a cost rating for each link to estimate degradation of communication effectiveness based on its LSF. The overall effectiveness of a layout is assessed by aggregating the cost ratings from all links into a single numerical score.

Layout solutions that are deemed optimal by LOCATE maximize inter-operator communication efficiency, which is a critical feature of military C2 spaces. However there are other social and psychological attributes that also influence the effective function of a collaborative workplace. For example, auditory distraction and a loss of speech privacy are common occurrences in shared workplaces that may lead to dissatisfaction and, in severe cases, performance degradation. Such factors are not represented in LOCATE.

1.2 Auditory distraction and speech privacy

A series of studies was conducted to examine workspace factors that affect their occupants' satisfaction [3, 4]. These studies analyzed the Post-Occupancy Evaluation (POE) database which is constructed and maintained by the Center for Built Environment (CBE), and evaluated users' satisfaction ratings with office layouts and environmental factors. Among sixteen factors that were investigated, auditory distraction and speech privacy were two leading factors for workplace dissatisfaction. In contrast, ease of interaction (i.e., a factor that's related to communication) was one of the least contributing sources. The findings are consistent for a number of common workspace layouts, including open-plan office settings. Beyond user satisfaction, the impact of noise on work performance has been documented [5]. Although many such studies were conducted in the civilian office environments, the general insights obtained from this literature are applicable to military environments. The objective of this study was to model the impact of auditory distractions, and to a lesser extent speech privacy, in the context of layout analysis. Both factors are related to speech intelligibility, with distraction reflecting a concern from a communication receiver whereas privacy from a source. If the traditional method in LOCATE tends to generate layouts that cluster operators together (so that inter-operator communication effectiveness is maximized), the consideration of auditory distraction and speech privacy will favor a more dispersed between-operator arrangement. By considering these factors together, we hope to create a modeling solution that generates balanced layout options that minimise auditory distraction without reducing communication efficiency, consequently improve overall operator satisfaction.

1.3 Research activities

To achieve the objective, the following research activities were conducted in this study:

1. Establish a framework for characterizing the effect of auditory distraction and speech privacy;

2. Identify performance moderators and an appropriate metric for quantitative examination of the impact of auditory distraction and speech privacy;

3. Develop an algorithmic method for incorporating speech intelligibility into workspace layout assessment with a goal for future implementation in layout modeling software; and

4. Demonstrate the feasibility of such a method in a series of sample use cases.

The scope of this study was focused on the auditory domain. A similar investigation for the visual domain was conducted in a separate study and was reported at Defence Research and Development Canada under contract with the C3HF Consulting Inc. [6]. This work was carried out on the basis of a prior study on auditory communication [7], and the output of which was incorporated in the proposed algorithmic solution.

2 A metric for speech intelligibility

In the context of layout analysis where the key design outcome is the location and orientation of individual operators and their workstations in the workspace, the common concerns associated with the auditory domain (i.e., communication, distraction and privacy) can all be investigated based on the same theoretical framework that is commonly articulated as the intelligibility of speech in noise. To facilitate communication, an acceptable distance between a speaker (source) and a listener (receiver) should enable sufficiently high speech intelligibility so that face-to-face conversation can be comfortably conducted. In contrast, to reduce auditory distraction and protect speech privacy, the proximity between a source and a receiver should be sufficiently extended so that low speech intelligibility can be accomplished. There exists a subtle difference between distraction and privacy concerns: distraction is viewed from the receiver's perspective whereas privacy reflects that of a source.

In this section, we first describe a generic model for describing direct speech communication. Such a model helps to shed light on the set of parameters that are required to analyze speech intelligibility. Then we explain two widely adopted speech intelligibility indices and select one that is deemed most appropriate for layout applications.

2.1 A model for direct speech communication

Figure 1 was adopted from ISO 9921:2003 which depicts a modular overview of direct communication between people [8]. Based on this model, speech communication is influenced by three factors: speaker, listener, and environment which correspond to input, output and transmission channel respectively.

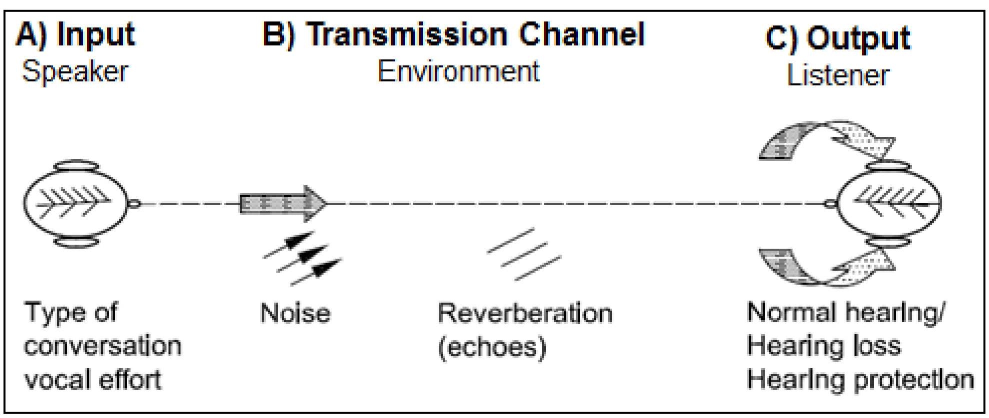

Figure 1: *A model of direct face-to-face speech communication, adapted from ISO 9921:2003, Figure D.1.*[1]

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A set of parameters are identified in this model for characterizing each factor, as listed below:

1. Speaker characteristics
    a. Vocal effort
    b. Speaking quality
    c. Gender
    d. Accents
    e. Non-native speech
    f. Speaking disorder
2. Listener characteristics
    a. Hearing aspects
        i. Directional hearing
        ii. Masking
        iii. Hearing disorders
        iv. Reception threshold
    b. Use of hearing protection
3. Transmission channel
    a. Ambient noise
    b. Reverberation
    c. Echoes
    d. Sound radiation
    e. Limitation in the frequency response
    f. Non-linearities

For layout analysis, the central concern is the proximity and directivity between a speaker and a listener. The characteristics that are typically associated with individual operators like hearing abilities are not subject to investigation as it is common to assume an average operator in a model with normal hearing. Environmental factors such as reverberation are also beyond the scope of layout modeling since such issues frequently fit into alternative acoustic analysis and mitigation solutions do not commonly involve the manipulation of layout. In this study, we've identified the following three parameters for consideration in an improved layout assessment solution:

- Speaker: vocal effort (level of speech signal)
- Environment: ambient noise
- Listener: distance (from speaker)

It is recognised that the consideration of these factors reflects a high level of simplification. However the granularity is sufficient for typical layout analyses. Additional factors can be introduced in the future if a high fidelity model is considered more desirable.

The common metric for assessing the quality of speech communication is intelligibility. Since such a metric is central for the development of an algorithmic assessment solution, we will describe this topic in a separate subsection.

2.2 Speech intelligibility metrics

Speech intelligibility is defined as a rating of the proportion of speech that is understood by a listener [9]. Common tests for intelligibility range from word segments, to rhyming words, to full sentences. A number of intelligibility measures have been developed, and comparisons among these indices have been extensively discussed (e.g., [8]). A previous DRDC study suggested that a metric that is based on the speech interference level is most suitable for layout analysis [7]. In this report, we will briefly explain the concept of speech interference level, following by a description of an alternative, Speech Transmission Index, which together were used in this study to develop the layout assessment procedure. Notably, equations described in this section are all adapted from the literature.

2.2.1 Speech interference level

The Speech Interference Level (SIL) was developed for rating noise with respect to speech interference. It is used for ergonomic assessment of person-to-person communication in a variety of environments including workplaces and meeting rooms [9]. Calculating SIL takes into account three factors that were identified in the previous subsection, that is, the vocal effort of a speaker, an average of the noise spectrum, and the distance between a speaker and a listener. Specifically, it is defined as the difference between A-weighted speech level[2] and the arithmetic average of sound pressure levels of ambient noise in four octave bands with central frequencies 500Hz, 1000Hz, 2000 Hz and 4000 Hz.

The following general procedure is suggested for estimating speech intelligibility based on the SIL.

[2] Background noise levels are often reported as A-weighted values. The A-weighting is a frequency weighting curve defined by the American National Standards Institute / Acoustical Society of America (ANSI/ASA) S1.4-1983(R2006) and the International Electrotechnical Commission (IEC) 61672-1:2013, designed to approximate the response of the human auditory system.

Step 1. Compute the *speech interference level* (L_{SIL}) at the listener's location, by a simple average of the noise spectrum at four octave bands,

$$L_{\mathrm{SIL}} = \tfrac{1}{4} \sum L_{\mathrm{N,oct,i}} \qquad \text{for i=1,2, 3, 4} \tag{1}$$

Step 2. Compute the *speech level* at the listener's position ($L_{S,A,L}$). In principle, $L_{S,A,L}$ is determined by the vocal effort of a speaker, which is commonly described by the equivalent continuous A-weighted sound pressure level of the speech at a distance of 1 metre (m) in front of the speaker's mouth ($L_{S,A,1m}$). Relationships between $L_{S,A,1m}$ and common terms for describing vocal effort are provided in Table 1.

Table 1: *Vocal effort of a male speaker and related A-weighted speech level (dB re 20 uPa) at 1m in front of the mouth, reprinted from ISO 9921:2003, Table A.1.*[3]

Vocal effort	$L_{S,A,1m}$ dB
Very loud	78
Loud	72
Raised	66
Normal	60
Relaxed	54

Besides vocal effort, $L_{S,A,L}$ is also influenced by other factors such as energetic (non-speech) and informational masking (speech) from background noise, the use of hearing protection, distance and language (e.g., fluency and accent). In this study, we focused on the distance factor since it is directly applicable to layout analysis, as shown below. The equation should be modified if other factors need to be considered.

$$L_{S,A,L} = L_{S,A,1m} - 20log_{10}(\frac{r}{r_0}) \tag{2}$$

where

$L_{S,A,1m}$ is the speech level at the speaker position,

r is the distance in meters between a speaker and a listener,

r_0 = 1m.

Step 3. Compute the parameter, *SIL*, that determines the speech intelligibility.

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$$SIL = L_{S,A,L} - L_{SIL} \tag{3}$$

Notably, both speech level and speech interference level are measured at the listener's position. According to ISO 9921, fair speech communication intelligibility is ensured if SIL is greater than 10dB at the listener's position (for normal-hearing, fluent listeners). For full documentation of SIL, readers are referred to [8].

2.2.2 Speech transmission index

The Speech Transmission Index (STI) is an objective method for rating the transmission quality of speech with respect to intelligibility. The rating assumes that the intelligibility of a transmitted speech signal is related to the preservation of the original spectral differences between speech sounds [8]. The STI method is widely applied to a range of electronic systems and acoustic environments. An STI rating that ranges between 0.0 and 1.0 (indicating zero to perfect speech intelligibility) can be directly measured by using modulated test signals. In the case of layout analysis, STI is not considered as a preferred measure since layout modeling often occurs during the conceptual design stage where parameters of the physical spaces are not yet fully available. However, a description of this measure is included in this report due to the following two reasons.

Firstly, a general relationship between work performance and speech intelligibility has been given using STI. Figure 2, which is adapted from [5], shows the effect of STI on the performance of cognitively demanding tasks. Such data is relevant to layout analysis since it makes it possible to articulate layout effectiveness in terms of operator performance. For example, an appreciable degradation of cognitive task performance can be expected (maximum 7%) when STI exceeds 0.6 and the degradation is minimal when STI is less than 0.2.

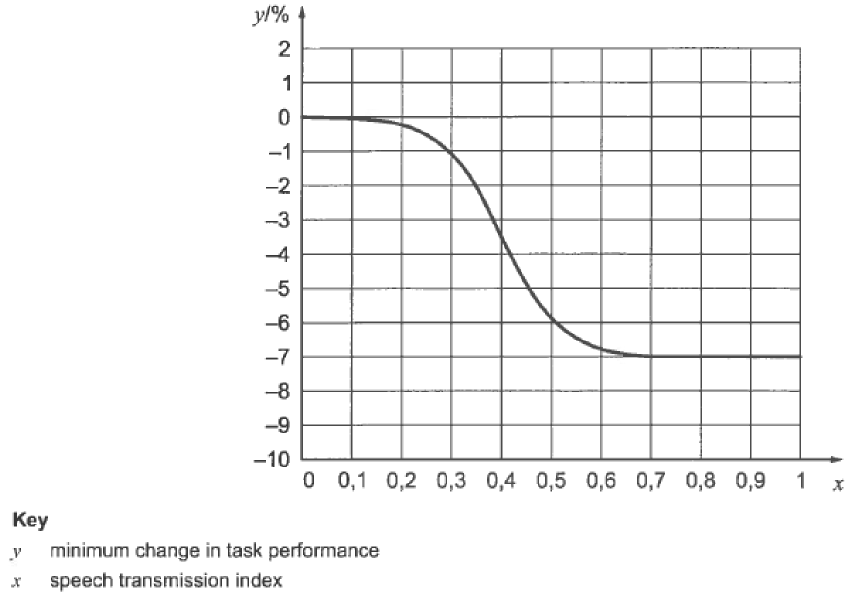

Figure 2: *The effect of STI on the performance of cognitive demanding tasks, reprinted from ISO 3382-3:2012.*[4]

Secondly, concepts such as distraction distance and privacy distance have been defined using thresholds expressed in STI. According to ISO 3382-3: 2012(E), the negative effects of speech on work performance start to vanish rapidly if the STI is below 0.5, therefore, a distraction distance has been set at the distance where STI reaches 0.5. From a listener's perspective, an increase of physical separation from a speaker beyond this threshold will lead to a rapid reduction in the STI rating and consequently auditory distraction caused by this speaker. Similarly, an STI rating of 0.2 is suggested for determining the privacy distance which reflects a concern of a speaker. When the speaker-listener separation is beyond such a distance, the listener can not hear much, the speaker's speech is considered private and the negative effect of such a speech on the listener's work performance is minimal.

Distraction distance and privacy distance concepts are central to our inquiry in this study. A comparison between various rating systems, see Table 2, allows us to estimate distraction and privacy distance criteria expressed in other metrics. For example, an STI value of 0.5 (for defining distraction distance) can be approximated with an SIL score of 12dB; an STI value of 0.2 (for defining privacy distance) with an SIL score of 3dB.

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Table 2: Intelligibility rating and relations between various intelligibility indices, adapted from ISO 9921:2003.[5]

Intelligibility rating	Sentence score %	Meaningful PB-word[3] score %	CVC_{EQB}-non-sense word Score %	STI	SIL dB	SII[4]
Excellent	100	> 98	> 81	> 0,75	21	
Good	100	93 - 98	70 - 81	0,60 - 0,75	15 – 21	> 0,75
Fair	100	80 - 93	53 - 70	0,45 - 0,60	10 – 15	
Poor	70 - 100	60 - 80	31 - 53	0,30 - 0,45	3 – 10	< 0,45
Bad	< 70	< 60	< 31	< 0,30	< 3	

It is noted that additional metrics, such as the Speech Intelligibility Index (SII), are also included in this table. The calculation of SII considers spectrum levels of speech and background noise, and hearing thresholds of a listener. Compared with the speech interference level, SII requires more detailed characterization of speech and noise which typically involves a wider range of frequency bands in the calculation [10]. For the purpose of layout modeling, the simpler procedure offered by speech interference level is considered preferable, and will be used in the next Section as the metric for layout evaluation.

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3 A proposed algorithmic method

The use of a speech intelligibility metric relevant to the workspace, like SIL, can be added to layout design cost ratings. An algorithmic method was developed in this study that represents a feasible way of incorporating SIL into layout assessments.

The proposed method involves a two-step analysis process. Step 1 focuses on communication requirements to ensure communication links (between all pair of speakers and listeners) are facilitated by their spatial locations. Step 2 emphasizes the reduction of potential auditory distraction and the enhancement of speech privacy, if such requirements are deemed important for the workplace.

3.1 Step 1: Speaker-centric assessment

The purpose of a speaker-centric assessment is to ensure that speakers are effectively heard by all intended listeners. This analysis is applied to all links where non-technology assisted auditory information exchange are required. For a speaker-listener pair between which no such a link is mandated, the assessment will not be performed.

The output from this analysis is prediction on minimal vocal effort (i.e., how loud a speaker needs to be) for each speaker in order for the intended listener(s) to hear clearly. Vocal effort, previously represented by $L_{\text{S, A, 1m}}$, will be abbreviated as VE when presenting vocal effort in the computational procedure. Based on equations presented in Section 2, the vocal effort of a speaker can be computed in the following way.

$$\begin{aligned} \text{VE} &= L_{\text{S, A, 1m}} \\ &= L_{\text{S, A, L}} + 20log_{10}(r/r_0) \\ &= SIL + L_{\text{SIL}} + 20log_{10}(r/r_0) \end{aligned} \tag{4}$$

where, SIL is a pre-defined speech intelligibility threshold for representing effective communication. As an example, a threshold of 10dB or 15dB could be adopted to represent *fair* or *good* speech intelligibility, according to Table 2:

L_{SIL} represents the speech interference level at the listener's position;

r is the distance in meters between a speaker and a listener; and

r_0 = 1 m.

In situations where a speaker is linked to more than one listener (i.e., multiple links), the required vocal effort could be estimated by adopting the largest $L_{\text{S, A, 1m}}$ score to indicate a worst case scenario. The prediction could be used to assess the quality of a particular link, since in many situations, a flag should be raised if the physical separation between a pair of operators forces the speaker to frequently communicate with elevated vocal effort beyond the normal level.

The algorithmic procedure for the speaker-centric analysis is described by the following list.

a. Identify all speakers in a layout model.

b. Identify all communication links that are associated with each speaker.

c. For each speaker, compute the required vocal effort for each associated link:

   i. Calculate the speech interference level at the listener's location, L_{SIL}.

   ii. Select an *SIL* threshold for judging the required level of speech intelligibility for this link.

   iii. Obtain the distance separation between a speaker and a listener (*r*), that is, the length of the link vector.

   iv. Compute the A-weighted speech level requirement, $L_{\text{S, A, 1m}}$, as below according to Equation (4).

$$L_{\text{S, A, 1m}} = L_{\text{S, A, L}} + 20log_{10}(r/r_0)$$

$$= SIL + L_{\text{SIL}} + 20log_{10}(r/r_0)$$

   v. Repeat Items i–iv if there are more than one link for the speaker.

   vi. Choose the largest $L_{\text{S, A, 1m}}$ value as an indication of the speaker's required vocal effort, that is,

$$VE = \max\{L_{S,A,1m}\} \tag{5}$$

d. Based on the required level of vocal effort, assess whether the layout arrangement between the involved speaker and listener is acceptable.

3.2 Step 2: Listener-centric assessment

The purpose of a listener-centric assessment is to reduce auditory distraction to a listener caused by unattended speech. A similar assessment can be used to analyze the speech privacy for a speaker as well in which case a more stringent speech intelligibility criterion should be adopted. Unattended speech can include conversations between other operators or public address announcements that are not intended for a particular listener. In general, such speech comes from speakers in a workplace whose positions are subject to layout design manipulation.

In our analysis, a speaker's speech is considered to be unattended when a communication link does not exist between the speaker and the listener. In such a situation, there is no need for conversation between the pair and consequently speech generated by the speaker is unwanted or irrelevant to the listener. For the purpose of the layout model, we use the term non-link to describe this relationship between a speaker-listener pair; if there does not exist a link, then we claim there is a non-link between them.

The listener-centric analysis is focused on all non-links for each listener. An *SIL* score is computed for each non-link and assessment could be performed to judge whether the distance separation is sufficient to reduce auditory distraction or protect speech privacy (i.e., based on thresholds translated from STI levels of 0.5 and 0.2, as discussed before).

Input parameters for this step of analysis include *SIL* at the listener's location (L_{SIL}), speaker-listener distance (r), and the speaker's vocal effort (VE) which is based on predictions made in the previous step of analysis.

The general procedure for the listener-centric analysis is described by the following list.

a. Identify all speakers in a layout model.

b. Identify all listeners in a layout model.

c. For each listener, identify all her non-links and compute an *SIL* score for each non-link:

    i. Calculate the speech interference level at the listener's location, L_{SIL}.

    ii. Obtain the vocal effort of the relevant speaker, based on calculation completed above in Step 1.

    iii. Obtain the distance separation between speaker and listener.

    iv. Compute the *SIL* score for the non-link, using the following solution transformed from Equation (4)

$$\begin{aligned} SIL &= L_{S,A,L} - L_{SIL} \\ &= VE - 20log_{10}(r/r_0) - L_{SIL} \end{aligned}$$

d. Assess the quality of layout for the particular non-link by comparing its *SIL* score with the pre-defined threshold (e.g., 10dB for reduced auditory distraction, 3dB for speech privacy).

3.3 Sample computational models

To illustrate how the algorithm works in a layout study, three fictitious situations are presented in this subsection to explain the proposed computational procedure. The following assumptions are adopted for all three models:

1. The ambient noise in the workspace is described using parameters from Table 3, which is used for characterizing noise levels at all listeners' locations.

Table 3: *A sample model of ambient noise in a workplace.*

Octave Band (Hz)	500	1000	2000	4000
Level (dB)	69.3	61.4	61.1	54.8

According to Equation (1), the speech interference level at a listener's location can be computed as:

$$L_{SIL} = 1/4 \sum L_{N,oct,\ i}$$

$$L_{SIL} = (69.3+61.4+61.1+54.8)/4$$

$$L_{SIL} = 61.7 \text{ dBA}$$

For the sake of brevity, this L_{SIL} value is applied to the entire workspace. In future applications where data of localized ambient noise levels are available, more accurate representation can be introduced into the model.

2. The acceptable *SIL* threshold for effective communication is assumed to be 15dB. According to Table 2, an *SIL* rating higher than this threshold corresponds to 'good' to 'excellent' speech intelligibility. This *SIL* threshold will be applied in Step 1 of the analysis where communicability between speakers and listeners are examined.

3. The acceptable *SIL* threshold for distraction distance is assumed to be 10dB. According to Table 2, an *SIL* rating lower than 10dB corresponds to 'poor' to 'bad' speech intelligibility. This *SIL* threshold will be applied in Step 2 of the analysis where distractions from unattended speech, or non-link, are evaluated. Of note, the method for assessing speech privacy is identical to auditory distraction. The only difference is that a more stringent *SIL* threshold is adopted for the privacy measure. Since privacy concerns are commonly less critical than distraction in routine military operations, they are not discussed in these examples.

3.3.1 Model 1—one speaker and two listeners

Figure 3 illustrates a simplistic model in which three entities (one speaker S1 and two listeners, L1 and L2) are represented. There is a single communication link in this model between S1 and L1 (denoted hereafter as S1L1), and no such a link exists between S1 and L2 (i.e., a non-link for S1\L2, note the use of a backslash to distinguish it from a link). The physical separation between S1 and L1 is arbitrarily defined as 2m, whereas the separation between S1 and L2 is 3m.

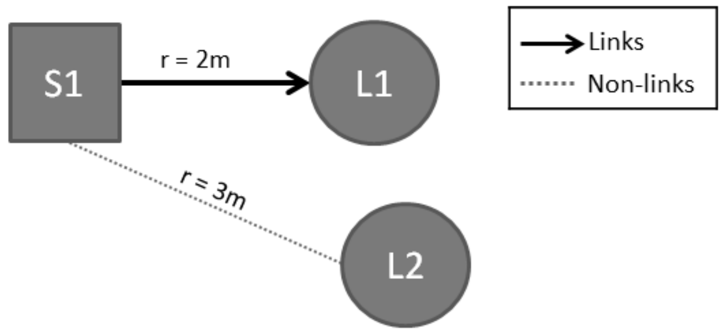

Figure 3: *A simplistic layout problem with one speaker and two listeners.*

According to the proposed layout evaluation algorithm, the first step of analysis is to predict the required vocal effort for all speakers in a layout model, based on all communication links that are associated with each speaker of interest. The detailed 2-step algorithmic method is described below.

Step 1, speaker-centric analysis

a. Identify all speakers in the layout model. In this case, a single speaker S1.

b. Identify all communication links that are associated with each speaker. For S1, there is a single link S1L1 in this model.

c. For each speaker, compute the required vocal effort for each associated link. In this case, link S1L1 for speaker S1:

   i. Calculate the speech interference level at the listener's location L_{SIL}. In this case, a generic noise level is applied to the entire workspace, L_{SIL} = 61.7 dBA, as described previously in assumption (1).

   ii. Adopt an *SIL* threshold for judging the required level of speech legibility for this link. In this case, according to assumption (2), an *SIL* threshold of 15dB is selected.

   iii. Obtain the distance separation between speaker and listener, that is, the length of link vector S1L1. This parameter is a result from a layout solution and is subject to design manipulation. In this case, r(S1L1) = 2m.

   iv. Compute A-weighted speech level requirement, $L_{S,\,A,\,1m}$, as below:

$$
\begin{aligned}
L_{S,\,A,\,1m} &= L_{S,\,A,\,L} + 20log_{10}(r/r_0) \\
&= SIL + L_{SIL} + 20log_{10}(r/r_0) \\
&= 15 + 61.7 + 6.0 \\
&= 82.7 \text{ dBA}
\end{aligned}
$$

v. Repeat Items (i–iv) if there are more than one link where S1 is the speaker. Choose the largest $L_{S,\ A,\ 1m}$ value as an indication of S1's required vocal effort VE(S1).

d. Qualitatively assess the required level of vocal effort and decide whether the layout arrangement between the involved speaker and listener is acceptable. For most layout solutions, the goal is to ensure a normal level of vocal effort ($L_{S,\ A,\ 1m}$ = 60dBA) is required for frequent conversations. In this case, under the specific ambient noise level, a vocal effort of 82.7dBA is predicted for the speaker to produce intelligible speech with a listener who situates 2m away. According to Table 1, 82.7dBA indicate a 'very loud' level of vocal effort, which is not desirable in most workspace settings.

Step 2, listener-centric analysis

After the speaker-centric analysis is completed, a follow-up listener centric analysis is performed to examine potential distractions to listeners caused by irrelevant speeches.

a. Identify all speakers in the layout model. In this case, a single speaker S1.

b. Identify all listeners in the layout model. In this case, two listeners L1 and L2.

c. For each listener, compute the *SIL* score with all speakers between whom there is not a communication link (i.e., for all non-links). In those cases, the speaker's speech is considered as unwanted sound thus a source of distraction to the listener of interest. In this model, L1 does not have a non-link, therefore no further analysis is required. For L2, a single non-link S1\L2 is identified, then the following procedure is adopted to calculate *SIL* score at L2's location, as caused by S1.

   i. Calculate the level of ambient noise (at the listener's location) L_{SIL}. In this case, a generic noise level is applied to the entire workspace, L_{SIL} = 61.7 dBA, as described previously in assumption (1).

   ii. Obtain the vocal effort of S1, based on calculation completed above in Step 1. In this case, VE(S1) = 82.7dBA.

   iii. Obtain the distance separation between speaker and listener, that is, the length of the link vector S1\L2. This parameter is a result from a layout solution and is subject to design manipulation. In this case, r(S1\L2) = 3m.

   iv. Compute the *SIL* score for non-link S1\L2 as

$$
\begin{aligned}
SIL(S1\backslash L2) &= L_{S,A,L} - L_{SIL} \\
&= (L_{S,\ A,\ 1m}) - 20log_{10}(r/r0) - L_{SIL} \\
&= 82.7 - 9.5 - 61.7 \\
&= 11.5 \text{ dB}
\end{aligned}
$$

d. Assess the quality of layout for the particular non-link by comparing its *SIL* score with the threshold defined in assumption (3). In this case, for S1\L2, an *SIL* score of 11.5dB is greater than the threshold 10dB, which indicates a suboptimal separation between S1 and L2.

3.3.2 Model 2—multiple speakers and listeners

Figure 4 shows a layout problem with increased complexity. In this case, two speakers (S1, S2) are present in the workplace, together with four listeners (L1 to L4). There are three communication links S1L1, S2L2, S2L3. No such links exist for all other pairing of speakers and listeners (i.e., non-links for S1\L2, S1\L3, S1\L4, S2\L1, S2\L4). Physical separations between speakers and listeners are labelled in the diagram. The analyses are broken down into the following steps.

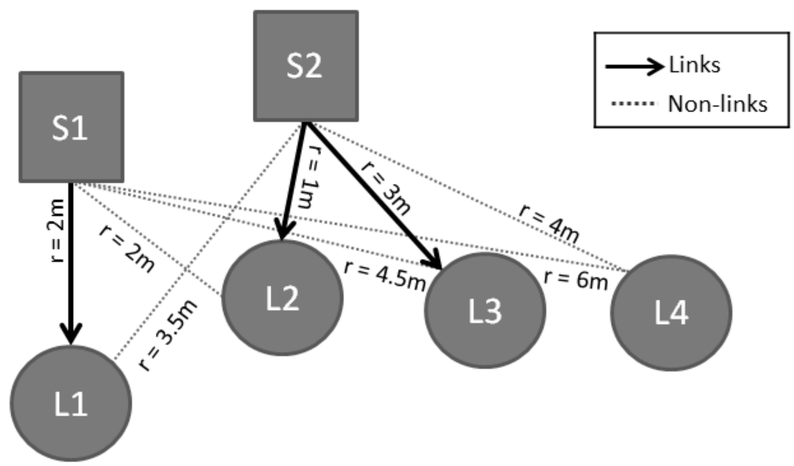

Figure 4: *A layout problem with multiple speakers and listeners.*

Step 1, speaker-centric analysis

a. Identify all speakers in the layout model. In this case, S1 and S2.

b. Identify all communication links that are associated with each speaker. For S1, there is a single link S1L1; for S2, there are two links S2L2, S2L3.

c. For each speaker, compute the required vocal effort for each associated link.

For S1, link S1L1:

L_{SIL} = 61.7 dBA

r=2m

$VE(S1L1) = L_{S,\,A,\,1m}$ = 82.7 dBA

Overall vocal effort level of S1 is equal to VE(S1L1) as there is a single link for S1.

$VE_{S1} = VE(S1L1) = 82.7$ dBA

According to Table 2, VE_{S1} is considered 'very loud' and is likely not desirable.

For S2, link S2L2:

$L_{SIL} = 61.7$

r=2m

$VE(S2L2) = L_{S,\ A,\ 1m} = 82.7$ dBA

Link S2L3

$L_{SIL} = 61.7$

r=3m

$VE(S2L3) = L_{S,\ A,\ 1m} = 86.2$ dBA

Overall vocal effort level of S2 is decided by selecting the largest $L_{S,\ A,\ 1m}$ scores, in this case,

$VE_{S2} = Max\ \{VE(S2L2),\ VE(S2L3)\} = 86.2$ dBA

According to Table 2, VE_{S2} is considered 'very loud' and is likely not acceptable.

Step 2, listener-centric analysis

a. Identify all speakers in the layout model. In this case, two speakers S1, S2.

b. Identify all listeners in the layout model. In this case, four listeners L1, L2, L3, L4.

c. For each listener, compute its *SIL* score with all speakers between whom there is not a communication link (i.e., for all non-links).

For L1, there is a single non-link S2\L1.

$$
\begin{aligned}
SIL(S2\backslash L1) &= L_{S,A,L} - L_{SIL} \\
&= (L_{S,\ A,\ 1m}) - 20 log_{10}(r/r_0) - L_{SIL} \\
&= 86.2 - 10.9 - 61.7 \\
&= 13.7 \text{ dB}
\end{aligned}
$$

Conclusion: given SIL(S2\L1) exceeds the 10dB threshold defined in our assumption, it is considered the separation between S2 and L1 unacceptable.

For L2, there is a single non-link S1\L2.

$SIL(S1\backslash L2) = L_{S,A,L} - L_{SIL}$

$= (L_{S,\ A,\ 1m}\ (S1)) - 20log_{10}(r/r_0) - L_{SIL}$

$= 86.2 - 6.0 - 61.7$

$= 18.5$ dB

Conclusion: given SIL(S1\L2) exceeds the 10dB threshold defined in our assumption, it is considered the separation between S1 and L2 unacceptable.

For L3, there is a single non-link S1\L3.

$SIL(S1\backslash L3) = L_{S,A,L} - L_{SIL}$

$= (L_{S,\ A,\ 1m}) - 20log_{10}(r/r_0) - L_{SIL}$

$= 82.7 - 13.1 - 61.7$

$= 7.9$ dB

Conclusion: given *SIL(S1\L3)* is less than the 10dB threshold defined in our assumption, it is considered the separation between S1 and L3 acceptable.

For L4, there are two non-links, S1\L4 and S2\L4.

$SIL(S1\backslash L4) = L_{S,A,L} - L_{SIL}$

$= (L_{S,\ A,\ 1m}) - 20log_{10}(r/r_0) - L_{SIL}$

$= 82.7 - 15.6 - 61.7$

$= 5.4$ dB

Conclusion: given *SIL(S1\L4)* is less than the 10dB threshold defined in our assumption, it is considered the current separation between S1 and L4 acceptable.

$SIL(S2\backslash L4) = (L_{S,\ A,\ 1m}) - 20log_{10}(r/r_0) - L_{SIL}$

$= 86.2 - 12.0 - 61.7$

$= 12.5$ dB

Conclusion: given *SIL(S2\L4)* is greater than the 10dB threshold defined in our assumption, it is considered the separation between S2 and L4 unacceptable.

3.3.3 Model 3—entities that serve as both speaker and listener

Figure 5 shows the third model where entities are introduced that should be modeled both as a speaker and a listener (coded here as SL). Such an entity is a more likely representation of human operators since few would function purely as a speaker or a listener in the workplace. In this model, three entities are modelled, SL1, SL2 and a listener L3. Note the link between SL1 and SL2 is bi-directional, indicating a bi-way speech communication path. The general assessment procedure remains the same, except in this model, we will have to consider SL entities as speaker and listener separately, as explained below.

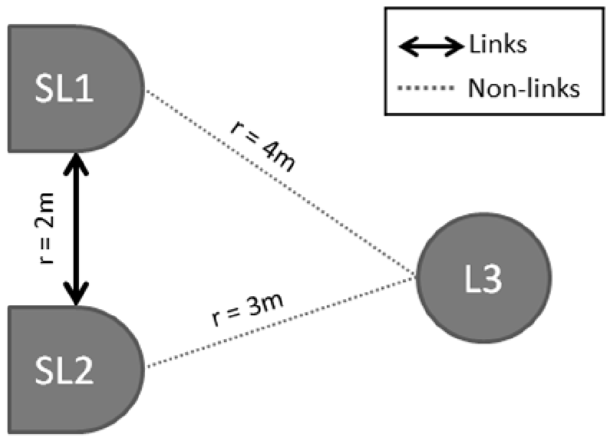

Figure 5: *Operators with both speaker and listener roles in determining VE and SIL*

Step 1, speaker-centric analysis

a. Identify all speakers in the layout model. In this case, SL1 and SL2.

b. Identify all communication links that are associated with each speaker. For SL1, there is a single link SL1SL2; for SL2, there is a single link SL2SL1.

c. For each speaker, compute the required vocal effort for each associated link.

For SL1, link SL1SL2:

L_{SIL} = 61.7 dBA

r=2m

$VE(SL1SL2) = L_{S,\ A,\ 1m}$ = 82.7 dBA

Overall vocal effort level of SL1 is equal to *VE(SL1SL2)* as there is a single link for SL1.

$VE_{SL1} = VE(SL1SL2)$ = 82.7 dBA

Conclusion: According to Table 1, VE_{SL1} is considered ‘very loud’ and is likely not desirable.

For S2, link SL2SL1:

L_{SIL} = 61.7

r=2m

$VE(SL2SL1) = L_{S,\ A,\ 1m}$ = 82.7 dBA

Overall vocal effort level of SL2 is equal to *VE(SL2SL1)* as there is a single link for SL2.

$VE_{SL2} = VE(SL2SL1)$ = 82.7 dBA

Conclusion: According to Table 1, VE_{SL2} is considered 'very loud' and is likely not desirable.

Step 2, listener-centric analysis

a. Identify all speakers in the layout model. In this case, two speakers SL1, SL2.

b. Identify all listeners in the layout model. In this case, three listeners SL1, SL2, L3.

c. For each listener, compute its SIL score with all speakers between whom there is not a communication link (i.e., for all non-links).

For SL1 and SL2, since there is no non-link, therefore the *SIL* calculation is not performed.

For L3, there are two non-links, SL1\L3 and SL2\L3.

$$SIL(SL1\backslash L3) = L_{S,A,L} - L_{SIL}$$

$$= (L_{S,\ A,\ 1m}) - 20log_{10}(r/r_0) - L_{SIL}$$

$$= 82.7 - 12.0 - 61.7$$

$$= 9.0 \text{ dB}$$

Conclusion: given *SIL(SL1\L3)* is less than the 10dB threshold defined in our assumption, it is considered the current separation between SL1 and L3 acceptable.

$$SIL(SL2\backslash L3) = L_{S,A,L} - L_{SIL}$$

$$=(L_{S,\ A,\ 1m}) - 20log_{10}(r/r_0) - L_{SIL}$$

$$= 82.7 - 9.5 - 61.7$$

$$= 11.5 \text{ dB}$$

Conclusion: given *SIL(SL2\L3)* is greater than the 10dB threshold defined in our assumption, it is considered the separation between SL2 and L3 unacceptable.

3.4 Limitations

The following issues should be discussed with respect to this proposed layout assessment algorithm.

1. The estimate of speakers' vocal efforts depends on their respective locations in the workspace. In a military C2 space, it is common for operators to move around, particularly senior officers who have a supervising role. To model such an operator, multiple speaker locations may be introduced with a prediction of vocal effort at each of these locations.

2. Predictions of speakers' vocal effort are approximation only. Individual differences are not considered, and other well-known phenomenon such as the Lombard's effect (i.e., an elevation of vocal effort in the context of increased ambient noise), or reduction of VE while wearing a hearing protection device [11], are not represented in the current algorithms.

3. The proposed method does not address auditory distractions to listeners caused by their collaborators, with whom there exists an auditory communication link. A common example of this circumstance is that a supervisor's conversation with one team member becomes a distraction to other team members. This reflects a dilemma in workplace design, and likely solutions will involve the use of other means beyond layout itself, such as the use of a noise reduction device when needed.

4. In principle, unattended speech could be regarded as a source of ambient noise and modelled as such, however they are represented differently in the proposed algorithm. The distinction is due to their treatment in layout analysis, with irrelevant speech associated with a speaker whose location is subject to layout manipulation, whereas general ambient noise only affects the calculation of speech interference levels at a listener's location. Additionally such a distinction was based on research findings that indicate irrelevant speech is more disruptive than white noise [12, 13].

5. Further investigation is needed to validate performance thresholds adapted in the proposed method. For example, a score of 70% was used in speech intelligibility metrics for indicating just reliable communication [9], it is debatable whether such a threshold is sufficient for military applications [7]. The vocal effort estimate (e.g., Table 1) is based on male speakers and adjustment is likely needed when female operators are represented in a model.

6. The proposed method is applicable to face-to-face auditory communication that does not involve electro-acoustic means. In many military applications however communication systems are widely used, one example is the operations room on a warship where operators frequently talk to one another on radio networks. Although our proposed method could still be applied for such a work environment (with a focus on face-to-face communication only), one adjustment is needed to account for the fact that many operators wear a headset which requires a further adjustment of speech intelligibility calculation. General guidelines on such adjustments have been provided before [8], it should be incorporated into the modeling method in the future.

4 Conclusion

In this study, we developed a layout assessment method based on the existing body of knowledge about direct face-to-face auditory communication and speech intelligibility metrics. Compared to LOCATE, the proposed method reflects improvement in two areas: Firstly the use of SIL provides a more tangible metric for layout assessment, compared to the unitless cost rating adopted in LOCATE. Based on predictions of all speakers' vocal effort, it is possible to estimate how noisy a workplace will be depending on its layout configurations. Secondly, the incorporation of auditory distraction and speech privacy measures enable layout assessment from a perspective that is important for improving workspace satisfaction, but has not been fully considered in existing layout modeling methodologies. If one considers the speaker-centric assessment an incremental improvement, the listener-centric assessment in the proposed solution reflects a more substantial expansion of the modeling capability.

The first-step of analysis (i.e., speaker-centric) tends to cluster operators in close proximity so that communication effectiveness is maximized, whereas the second-step (listener-centric) generally would push operators apart to reduce or eliminate distraction and increase speech privacy. By applying such a method to military C2 space design, the preferred solutions tend to be pod-like layouts where operators of the same functional team are grouped together in a pod and physical separations are introduced between functional teams (pods). Such designs were found to be preferable in several recent layout studies [14].

It is useful to note the proposed two-step analysis can be tailored for specific project needs. For example, if auditory distraction is not a concern for a particular work environment, the listener-centric assessment can be omitted. More commonly in military C2 spaces, speech privacy is not considered an important requirement, as a result the appropriate *SIL* threshold should be chosen in the listener-centric assessment to emphasize the reduction of distraction, rather than protection of speech privacy. The proposed solution will be further tested and eventually incorporated into a layout modeling software. Currently, prototype development has been on-going based on an open source platform, named SweetHome 3D. Research plans have also been established to conduct a noise survey and a communication survey for critical control spaces onboard of a modernized Canadian Patrol Frigate, such surveys will support more realistic modeling of ambient noise levels and communication patterns. The incorporation of the proposed solution into future modeling software will allow a more comprehensive representation of operator requirements in naval C2 spaces and facilitate the development of effective workspace layouts to satisfy such requirements. This layout design assessment technique has implications beyond the navy and may be applied to all types of military workspaces that involve auditory communications such as crews within vehicles, dismounted soldiers, as well as operational level headquarters.

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List of symbols/abbreviations/acronyms/initialisms

ANSI	American National Standards Institute
C2	Command and Control
CBE	Centre for Built Environment
dBA	Decibels, A-weighted, sound pressure level
DRDC	Defence Research and Development Canada
$L_{S, A, 1m}$	Equivalent continuous A-weighted sound-pressure level of the speech at a distance of 1m in front of the mouth
$L_{S,A, L}$	Equivalent continuous A-weighted sound-pressure level of the speech at the listener's ear
$L_{N,oct, i}$	Octave pressure level of the ambient noise at the listener's ear in octave band "*i*"
L_{SIL}	Speech interference level of the noise at the listener's ear
POE	Post-Occupancy Survey
RCN	Royal Canadian Navy
SII	Speech Intelligibility Index
SIL	Speech Interference Level
SNR	Signal-to-Noise Ratio
STI	Speech Transmission Index

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Creating a workspace layout for effective collaboration is important for critical Command and Control (C2) spaces. Computational models have been proposed to address this requirement, offering a mathematical method to analyze the effectiveness of communication within such collaborative environments. With an objective to improve an existing DRDC layout modeling tool, LOCATE, this study was performed to investigate the use of speech intelligibility indices for measuring communication effectiveness, as well as two other factors (auditory distraction and speech privacy) that influence users' satisfaction with their workspace. Based on a literature survey, the speech interference level was identified as a preferable metric for intelligibility measure and a two-step algorithmic method was proposed to analyse layout effectiveness based on the perspectives of both speakers and listeners. Three sample models were presented in this report to describe the computational procedure for the proposed method. Future incorporation of this method into a software tool will enhance DRDC's capability in workspace layout modelling.

Il importe d'aménager un espace de travail favorisant une collaboration efficace dans les postes névralgiques de commandement et contrôle (C2). Les modèles informatiques proposés pour répondre à ce besoin offrent une méthode mathématique pour analyser l'efficacité des communications dans de tels environnements de collaboration. Dans le but d'améliorer LOCATE, un outil de modélisation de l'aménagement utilisé actuellement par RDDC, la présente étude explore le recours à des indicateurs d'intelligibilité de la parole afin de mesurer l'efficacité des communications, ainsi que deux autres facteurs (distraction auditive et confidentialité des entretiens) qui ont une incidence sur la satisfaction que tire l'utilisateur de son espace de travail. La revue de littérature révèle que le niveau d'interférence avec la parole est la mesure privilégiée de l'intelligibilité, et une méthode algorithmique en deux étapes est proposée pour analyser l'efficacité de l'aménagement du point de vue du locuteur et de l'auditeur. Trois exemples de modèles sont décrits dans le présent rapport pour énoncer la procédure de calcul sur laquelle repose la méthode proposée. L'intégration de cette méthode à un outil logiciel permettra d'accroître la capacité de RDDC en matière de modélisation de l'aménagement de l'espace de travail.

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Workspace layout; Communication modelling; Algorithmic Solution