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Effects of Changing the Amount of Absorption in a Computer Model of Queen's Hall, Copenhagen, Denmark

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EFFECTS OF CHANGING THE AMOUNT OF ABSORPTION IN A COMPUTER MODEL OF QUEEN'S HALL, COPENHAGEN, DENMARK

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1 INTRODUCTION

Room acoustics computer modelling has become an important tool for acousticians and researchers over the last few decades. Several software programs exist and have been repeatedly tested and compared.[1,2,3,4] The aim of this research is to improve room acoustics computer modelling by developing a better understanding of the effects of including source directivity. This project focuses on a method that involves using multi-channel anechoic recordings to create multi-channel auralizations. Impulse response (IR) calculations and subsequent auralizations were made using models of an existing hall with varying amounts of absorption in ODEON. The IR calculations are used to compare the differences in the calculated objective parameters of reverberation time (T30) and sound pressure level (SPL) when using four and thirteen channels. Next, subjective testing is conducted to determine if subjects are able to differentiate source orientations from multi-channel auralizations produced for rooms with variable absorption qualities. Subjects' ratings of listener envelopment are additionally correlated to the objective parameter of late lateral sound energy, LG_{80}^{∞}.

2 PREVIOUS RESEARCH

2.1 Multi-Channel Auralization Method

Previous work by Otondo and Rindel[5] has shown that the distribution of common room acoustic parameters, such as SPL, in a modelled hall vary drastically depending on the assigned source directivity. Subjective testing confirmed the objective results, in that subjects could detect differences in loudness from auralizations made with the various impulse responses from different source directivities. Further work by Otondo and Rindel[6] has explored the use of multi-channel anechoic recordings to create multi-channel auralizations. Rather than include the source directivity at the impulse response calculation stage, the directional characteristics of the source are included at the convolution stage of the auralization process. Multi-channel anechoic recordings of short melodies were obtained for several instruments using 13 microphones. In order to obtain the appropriate impulse responses to convolve with the anechoic recordings, an omni-directional source is divided into equal sections equalling the number of recording channels. For instance, for the case of a four channel recording, the omni-directional source would be split into quadrants. The IR for each quadrant is then calculated and convolved with the appropriate recording channel. All four auralizations are then mixed to create a final multi-channel auralization. Otondo and Rindel used this procedure to create auralizations with one, two, five, and ten channels. Subjective tests were conducted where subjects were asked to evaluate both spaciousness and naturalness of timbre. The results showed that subjects found the auralizations to have higher degree of naturalness of timbre with an increasing number of channels. The results for the spaciousness evaluation were inconclusive.

The current study builds upon this work by comparing objective quantities using four and thirteen channels. Additionally, subjective tests are run where clarity and listener envelopment are evaluated with thirteen-channel auralizations, made with different source orientations and room absorption scenarios.

2.2 Listener Envelopment

The sense of spatial impression was first reported by Marshall[7] who described it as spatial responsiveness, where the opposite was expressed by the manager of the Concertgebouw Orchestra of Amsterdam as the "feeling of looking at the music". Barron[8] investigated this effect further and concluded that early reflections for up to 80 ms were perceived differently than reverberation. He conducted subjective tests using a single side reflection and evaluated the effects of tone colouration, echo disturbances, and spatial impression. The largest effects were found in differences of spatial impression and Barron coined the term in this paper. Barron and Marshall[9] continued to pursue this topic and found subjective differences in sensations from sounds at different frequencies. Lower frequencies tended to give more of an impression of being surrounded by the sound. The upper limit of 80 ms for early reflections was confirmed in this work and the objective measure of lateral energy fraction, LF_0^{80}, was defined. They also determined that spatial impression is a function of reflection angle.

Bradley and Soulodre[10] separated the effects of spatial impression into two distinct dimensions: apparent source width (ASW) and listener envelopment (LEV). Subjective testing revealed that LF_0^{80} is related to ASW and that it is harder to detect differences in ASW when there are increasing levels of reverberant energy. They found that the sense of LEV increased when a sound burst was added to the signals after 80 ms and the level of the burst was increased. Similar to Barron's findings, LEV was shown to be a function of angle of arrival. Subjective testing was conducted to determine if any correlations existed with an objective parameter and the subjective impression of LEV. Both the late lateral energy fraction, LF_{80}^{∞}, and the late lateral sound energy, LG_{80}^{∞} (equation 1), were found to correlate with LEV, with the latter having a higher correlation.

$$LG_{80}^{\infty} = 10\log\left[\int_{80}^{\infty} p^2(t)\cos^2(\alpha)dt \Big/ \int_{0}^{\infty} p_A^2(t)dt\right] \qquad (1)$$

The term *p(t)* is defined as the impulse response of the room, *α* is the angle between the arrival direction of a reflection and the line connecting a listener's ears, and $p_A(t)$ is the response from the same source measured at a distance of 10 m in a free field.

The late lateral sound energy can be given as a single number summed over the A-weighted values for the six octave bands of 125 Hz to 4 kHz. Further research was pursued by Bradley and Soulodre[11] to refine this parameter. Subjective testing revealed that using an unweighted LG_{80}^{∞} averaged over four octave bands of 125 Hz to 1 kHz had the highest correlation to subjective impression of LEV.

3 METHODOLOGY

3.1 Computer Modelling

Computer modelling was used to evaluate the effects of multi-channel source material in a room with different absorption qualities. The calculations were carried out in ODEON and a model of Queen's hall was utilized. This hall is an existing small auditorium, located in Copenhagen, Denmark, which has a variable number of seats between 400 – 600. The model has maximum dimensions of 30.2 m X 18.2 m X 10.8 m and is composed of 91 surfaces, as shown in Figure 1.

The room acoustic parameters were calculated using ODEON v6.5, while the auralizations were created with v8.0. The actual hall has variable acoustics, which was incorporated into the model. Four levels of absorption were investigated. The first is referred to as the ‘reflective’ state, in which the primary absorptive surface is the audience area seating. The average reverberation time (RT_{avg}) across the 500 Hz, 1 kHz and 2kHz octave bands is 2.04 s. The second level of absorption includes absorption on the back stage wall or SA for stage absorption (RT_{avg} =1.77 s). The third level (RT_{avg} =1.14 s) includes the variable absorption on the side walls only (SWA), while the final level includes both the stage and side wall additional absorption (SSWA, RT_{avg} =0.92 s).

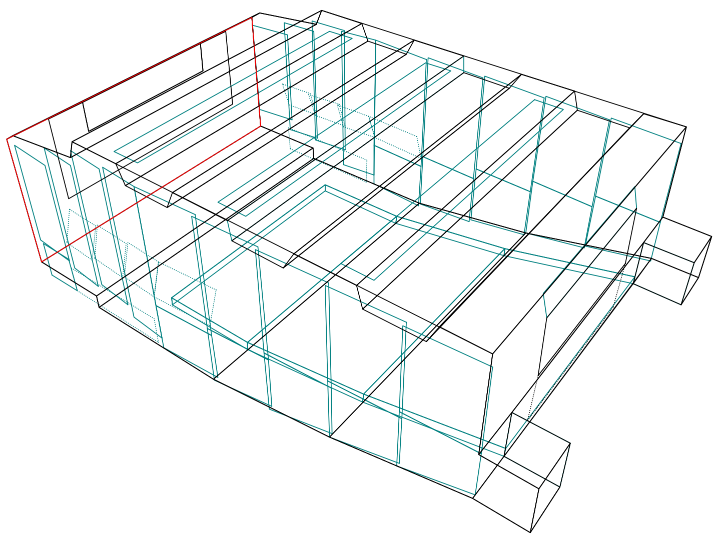
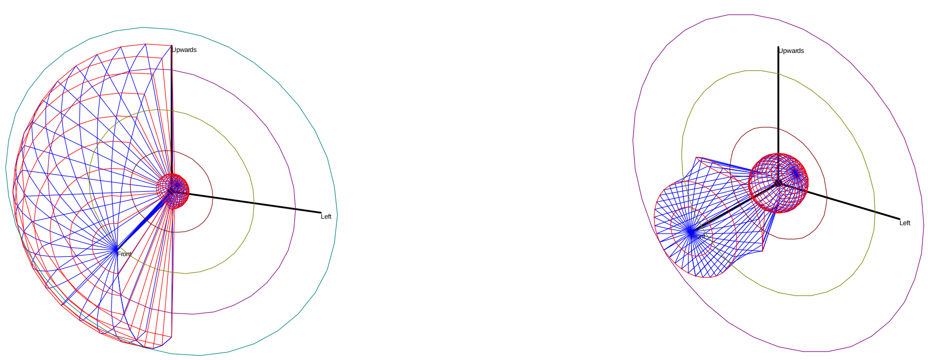


Figure 1 – ODEON model of Queen’s Hall.

Binaural impulse responses (BRIRs) were calculated using sources that radiate into both one-fourth and one-thirteenth of a sphere; see Figures 2a and 2b, respectively. Reverberation time and sound pressure level were then derived from these impulse responses to characterize the rooms and examine the differences between the four quadrant sources and the thirteen ‘thirteenth’ sources.



(a) (b)

Figure 2 – Sources used in computer modelling study: (a) quadrant, and (b) thirteenth.

Subjective Testing

Auralizations were created by convolving the BRIRs of the thirteenth sources with two short melodies. The thirteen individual auralizations for each room and instrument were mixed in ODEON to create multi-channel auralizations. One goal of the testing was to determine if subjects could identify source orientation, i.e. when the source is facing the audience and facing away from the audience, from these multi-channel auralizations of rooms with different levels of absorption. The hypothesis was that the source directivity, and consequently source orientation, would be more apparent in more absorptive rooms. This test was administered by having the subjects rate clarity on a scale from 1 to 7, where 1 is not clear and 7 is very clear. Additionally, subjects were asked to evaluate the listener envelopment of the auralizations. A similar rating scale was used, where 1 represented feeling not immersed in the sound and 7 represented feeling very immersed in the sound.

A single source/receiver location combination was used for all of the auralizations. The melodies used in the study were recorded from solo flute and solo violin. These instruments were chosen to represent a very directional source (flute) and a less directional source (violin). A total of 16 auralizations were made, using the model with four levels of absorption, two instruments, and two orientation directions with the source facing the audience (front) or facing away from the audience (back). Thirty subjects participated in the study with an equal number of males and females. The hearing thresholds of all subjects were measured prior to participation to ensure they had levels below 25 dB at six octave bands from 250 Hz to 8 kHz. All subjects had a minimum of three years of musical training, as it is postulated that musicians have higher thresholds for distinguishing small differences in auralizations.[12]

Before commencing the testing, all subjects completed a short tutorial describing the properties of clarity and listener envelopment. Example auralizations were also included to demonstrate a few conditions for each property. Subjects were then presented all 16 auralizations twice over Sennheiser HP-60 headphones, in addition to four practice tracks at the beginning of the testing session for a total of 36 auralizations. The practice tracks were used, since it has been shown that it takes subjects some time to adapt to the testing procedure.[13] Subjects each received a unique random presentation order of the auralizations. The testing was conducted in an isolated office with a low background noise level of approximately 35 dBA. The auralizations were presented to the subjects at a level of approximately 65 dBA.

4 RESULTS

4.1 Computer Modelling – Reverberation Time and Sound Pressure Level

The impulse responses for the quadrant and thirteenth sources were computed for the four levels of room absorption. The resulting reverberation times (T30s) and sound pressure levels (SPLs) were calculated for each of the sources. The results for T30 for the quadrant (Front, Right, Back, Left) and thirteenth sources are shown in Figures 3 and 4, respectively. The just noticeable difference (JND) for reverberation time was set to 5 %. The largest difference between individual sources was found in the the SWA room for the quadrant sources and the reflective room for the thirteenth sources, with differences of 6.5 and 3.8 JNDs, respectively. The results do not indicate a trend of decreasing JNDs as the room absorption level increases, though. Therefore, the importance of source directivity does not diminish as the room becomes more absorptive. Similar results were found for SPL, with an average of 1.05 JNDs across rooms for the quadrant sources and an average of 3.5 JNDs for the thirteenth sources, where the JND for SPL was set to 3 dB. The difference in JNDs increased for the case of the thirteenth sources as compared to the quadrant sources.

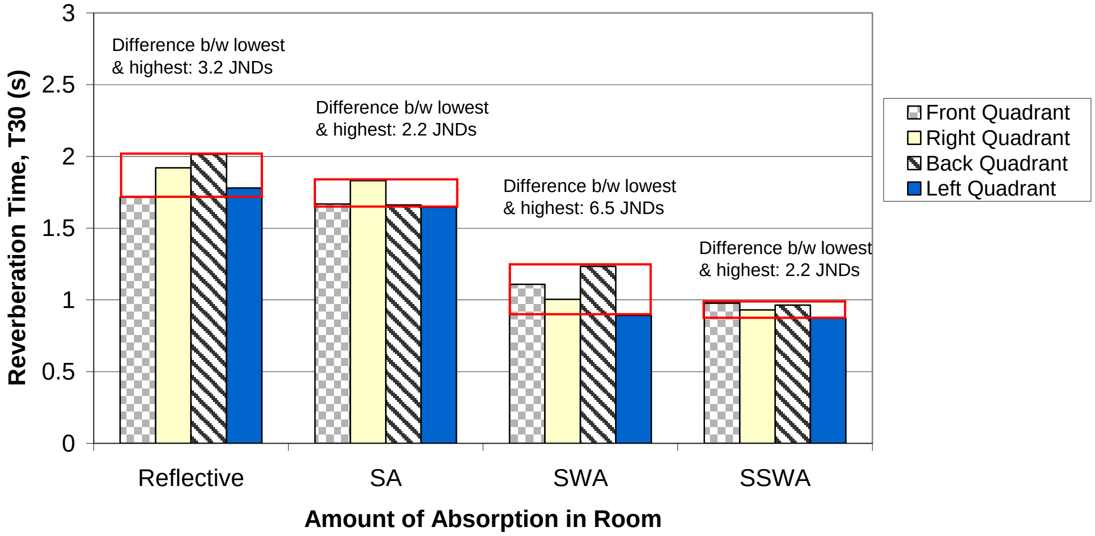


Figure 3 – Reverberation time results for each of the **quadrant** sources for each level of absorption in the model.

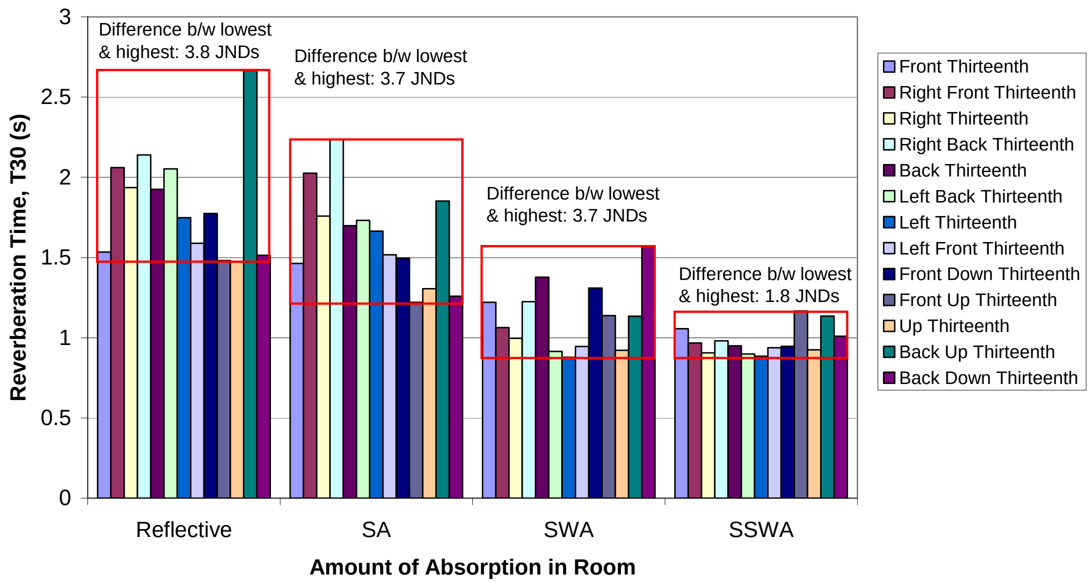


Figure 4 – Reverberation time results for each of the **thirteenth** sources for each level of absorption in the model.

4.2 Subjective Testing – Source Orientation and Listener Envelopment

The results from the subjective testing were analysed using a repeated measures analysis of variance (ANOVA). The experimental design was a 4 (room levels) X 2 (instrument) X 2 (orientation) X 2 (repetition) factorial design. For the first test, which evaluated subjects' ability to identify source orientation based on clarity ratings, no significant results were found as a function of orientation. Still, the data did show a trend that subjects rated the auralizations made with the source facing the front as clearer than when the source was facing away. A significant linear trend was found in that clarity rating increased as the room's absorption increased, as expected (mean values for each case were M_{Ref}=4.57, M_{SA}=4.78, M_{SWA}=5.20, M_{SSWA}=5.34), $F(1,29)=10.49$, $p < .002$. Another significant main effect was found based on instrument type, in that the violin auralizations (M=5.29) were rated as clearer than the flute auralizations (M=4.65), $F(1,29)=12.45$, $p < .002$, as shown in Figure 5. The result is surprising, as the flute is much more directional and one might expect it to create a clearer sound than the violin. A significant effect of repetition was not found, indicating that the subjects were consistent when they rated each track twice.

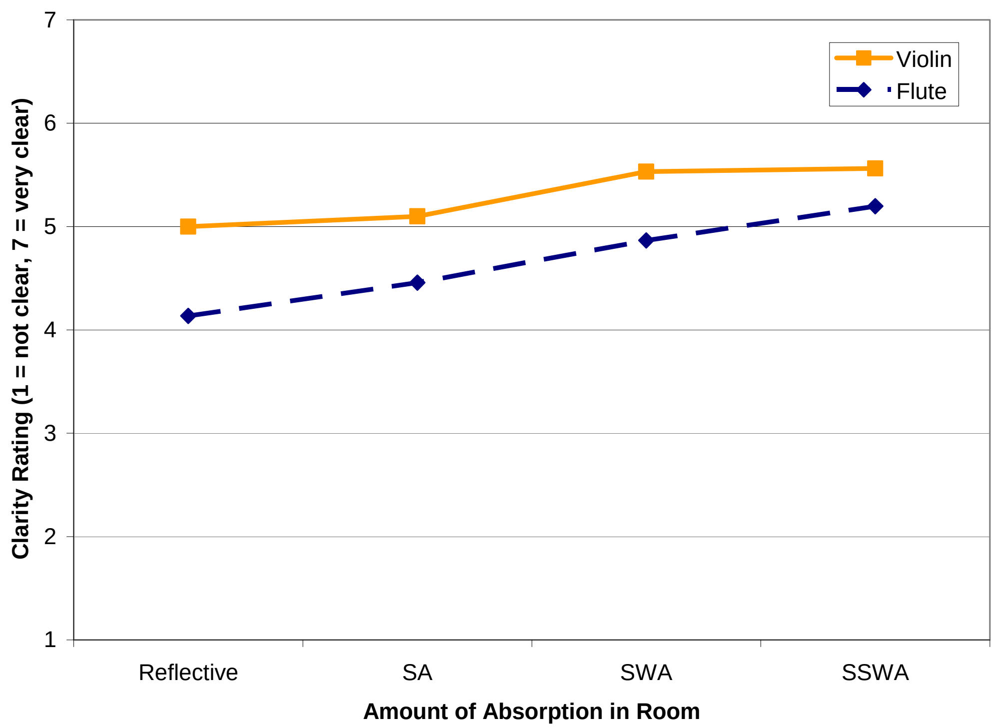


Figure 5 – Clarity ratings for both the flute and violin auralizations averaged over orientation shown as a function of the amount of absorption in the room.

The listener envelopment ratings demonstrated a significant effect where subjects rated that they felt less immersed in the sound as the absorption in the room increased, $F(1,29)=42.81$, $p < .0001$, as shown in Figure 6. This trend correlates with the calculated LG_{80}^{∞}, averaged over 125 Hz to 1 kHz, since this value decreased as the room's absorption increased (Reflective LG_{80}^{∞} = 19.1 dB, SA LG_{80}^{∞} = 18.1 dB, SWA LG_{80}^{∞} = 15.3 dB, SSWA LG_{80}^{∞} = 14.5 dB). This result supports previous findings that LG_{80}^{∞} is a good objective measure of LEV. The subjective listener envelopment results also show a significant trend with orientation, $F(1,29)=12.16$, $p < .002$, unlike the clarity test.

Subjects found the auralizations made with the front orientation (M=4.50) more enveloping than those made with the back orientation (M=4.18). The listener envelopment results certainly suggest that multi-channel auralizations are a useful tool for reproducing the varying degrees of this subjective quality.

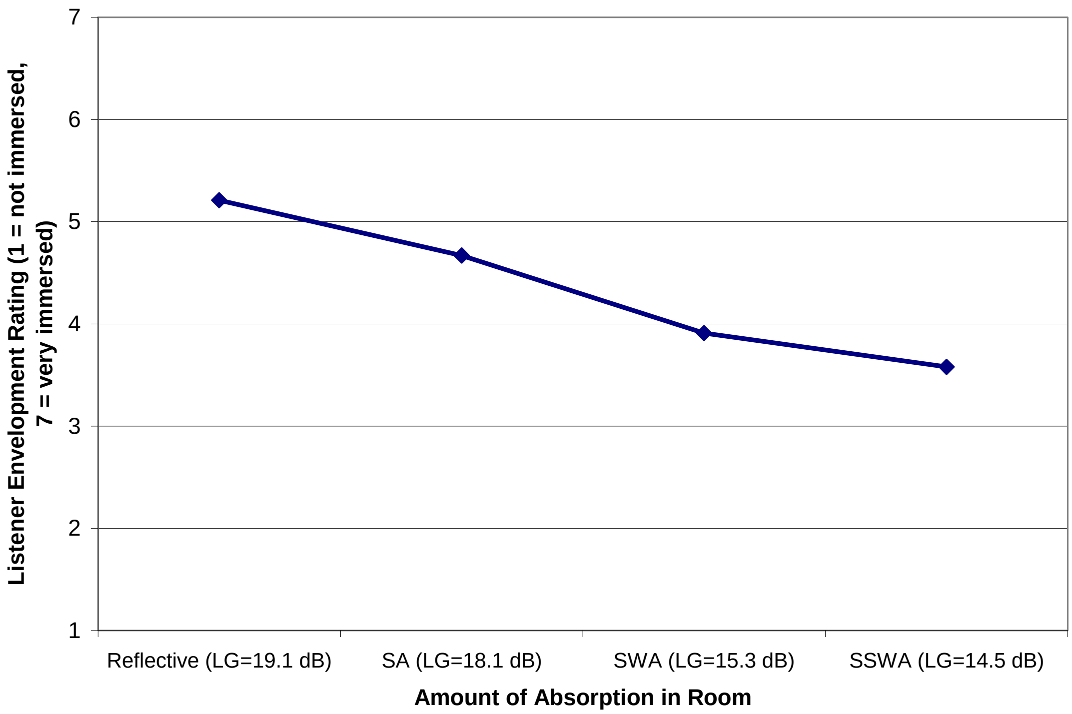


Figure 6 – Listener envelopment ratings averaged over the flute and violin auralizations and over orientation shown as a function of the amount of absorption in the room.

5 CONCLUSIONS

The initial part of the investigation revealed significant differences in both reverberation time and sound pressure levels when quadrant and thirteenth sources were used. The number of JNDs between the extreme values within each level of absorption stayed relatively constant across the different levels of absorption in each room. This result indicates the importance of incorporating accurate source directivity information into a computer model despite the absorptive nature of the room. The second part of the study investigated the subjective impression of the effect of source orientation on the room with varying levels of absorption. The orientation was evaluated using the objective measure of clarity. Overall, subjects were not able to correctly identify orientation at a significant level. However, trends in the data do show that they did correctly identify the increase in clarity across rooms with increasing levels of absorption. The clarity data also indicated that subjects rated the auralizations of the violin, considered the less directional instrument, as sounding clearer than those made with the flute. For the parameter of listener envelopment, subjects perceived the decreasing levels of LEV, which corresponded to the calculated values of LG_{80}^{∞}. There was also a significant effect of orientation, in that subjects rated auralizations created with the front orientation as sounding more enveloping than those created with the back orientation. Overall, using the multi-channel method to model source directivity does seem to accurately reproduce changing subjective qualities in rooms with different absorption characteristics.

6 ACKNOWLEDGMENTS

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