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Synergy Between Visual and Auditory Signals and Its Influence on the Follow-Up Regulation Quality

Jerzy Słowikowski
Marek Dźwiarek
Maria Konarska

Central Institute for Labour Protection – National Research Institute, Poland

The study aimed at verifying a hypothesis that supporting a visual signal of regulation deviation with an auditory one could improve the quality of regulation; the operator would have better information on machine operation. A special simulator was applied to follow-up tracking with a manual lever which controlled vertical movements of a cursor on a monitor screen. Simultaneously with visual information on screen, the operator was provided with an auditory deviation signal of pre-determined characteristics. 33 young males underwent the test. It was found that supporting a visual signal with an auditory one resulted in an improvement in the regulation quality by 5–6%, which proved synergy between those signals. The results may be used in designing tele- and servo-mechanisms, especially for remote control machinery, e.g., inspection robots or micromanipulators controlled by operators in a follow-up system.

quality of control   perception

1. INTRODUCTION

1.1. State of the Art

A technical object is considered as user-friendly when, in general, it can be operated in an easy way doing the things it is supposed to do; even the operator's positive feelings in the course of operation is important. All these aspects affect the reliability of a human–machine system [1]. Human–machine communication (or interface) is a crucial problem with two aspects. On the one hand the operator has to understand received information and its processing, and enter the decision into the machine. On the other hand actuators should be appropriate for the operator's movement and indicators should be appropriate for human perception. The regulation process, with an operator considered as an element of the regulation system, consists of a series of changes where regulation action is preceded by a signal perception act.

The present stage of machine technology makes it possible to support an operator's regulation actions with servo-mechanisms with an external power supply [1]. Supporting regulation equipment allows the operator to exert force and attain speed of a few orders of magnitude higher than those reached without support. This, however, involves strong emotional reactions (stress), especially when operators instead of sensing the effects of the undertaken action directly (as a force imposed

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Correspondence and requests for offprints should be sent to Marek Dźwiarek, Central Institute for Labour Protection – National Research Institute, Czerniakowska 16, 00-701 Warszawa, Poland. E-mail: <madzw@ciop.pl>.

on their body) can only monitor results indirectly with other senses, e.g., by looking at the results or by reading an indicator.

Machine design makes it important to take into consideration some properties of the human perception system; e.g., stimulus thresholds should be considered when dealing with a supported regulation system. At the first stage of development undertaken in scientific centres, research projects in psychological engineering have recently received much attention of the industry, mainly due to applicability of the results to raising competitiveness on the market. Leading companies have attempted to solve the problem of perception using computers for operators, e.g., of construction equipment, in which a regulation system is supported by a hybrid, digital–hydraulic system.

Computer simulation successfully applied in occupational biomechanics, especially to static and dynamic loads, unfortunately fails to determine dynamic regulation processes, including human–machine interface [2, 3]. Such complicated multidimensional problems of ergonomic optimisation are usually solved using simulators that register operators' reactions to various simultaneously applied external forces.

Simulation often consists in a visualisation of the regulation process, in which operators' actions—correct cursor movements, in this case—are taken. This method makes applying a well-defined excitation model possible. Regulation actions are usually modelled using follow-up tracking [4, 5, 6].

Research projects involving simulation of ergonomic parameters of servo-mechanisms and tele-manipulators have been conducted, among others, in Poland. Regulation system ratios were investigated at the Academy of Physical Education, Wrocław, in the late 1990s [7]. In the late 1980s and early 1990s a research project was conducted at the Institute of Industrial Design, Warszawa, on the combined influence of four variable parameters, regulation system ratio and inertia, and actuator type and size form in the context of their optimisation [8]. A research project in this field was also completed at the Central Institute for Labour Protection – National Research Institute (CIOP-PIB) using a third-generation simulator (see section 2.2.). This project aimed to determine the relation between the range of movement of the handle of a manual regulation lever and the force required to do guide it [1, 9]. In this research, a "behavioural" criterion was applied, i.e., regulation quality, with the use of vision to send feedback information during the process of follow-up tracking [10].

Supporting a visual deviation signal with other signals requiring the use of operators' other senses has been attempted. A visual signal supported with an additional tactile signal has been investigated, too [8]. Researchers at the Perception Institute in Eindhoven, The Netherlands, have studied the support of a visual signal with an auditory signal [9, 11]. The results of both experiments proved an inter-relation between visual and auditory or tactile signals.

1.2. Research Aims and Hypotheses

Since visual stimuli dominate operators' perception these authors tried to support vision by combining visual and auditory deviation signals in providing feedback on instantaneous deviation error. The basic hypothesis was that support of a visual deviation signal with an auditory signal synergetically improved regulation quality.

2. TESTING METHOD

2.1. Criteria of Regulation Quality

Regulation quality criteria used in the theory of regulation can be used to evaluate and objectively determine the ergonomics quality of regulation systems of such machines as tele- and servo-mechanisms, in which the correspondence between task execution time and errors is clearly visible. The integral criterion of instantaneous deviation in follow-up regulation is the most appropriate one.

Criteria in the theory of regulation have to meet two requirements important for a researcher investigating a human–machine system:

- they should accurately describe real behaviour of a human–machine system, taking into account correspondence between time and regulation deviation;

- both elements of the system, i.e., the human and the machine should use the same approach.

In the criterion used in the present work, the regulation error reads

$$U = \int_0^{t_{ex}} \left|(x_t - x_{t.\text{stat}}\right| dt, \quad (1)$$

where U—regulation error; t_{ex}—test time; x_t—instantaneous value of deviation; $x_{t\ \text{stat}}$—static deviation (in these test results $x_{t\ \text{stat}} = 0$, i.e., the whole area under the curve is taken into account).

The regulation error is a measure of regulation quality. For the purpose of this study it is assumed that regulation quality Q is inversely proportional to the regulation error:

$$Q = \frac{a}{U}, \quad (2)$$

where

$$a = \overline{U}_{\min}, \quad (3)$$

where $\overline{U}_{\min}$ is the minimum value of the regulation error observed in tests of a given regulation system.

For the j-th configuration of parameters, Q can be written as follows:

$$Q_j = \frac{\overline{U}_{\min}}{\overline{U}_j}. \quad (4)$$

Q_j remains within the limits $0 < Q_j \leq 1$. For a designer using the test results this means that in a given design the regulation system parameters should be the same or closest in value to those that provided the best regulation quality.

2.2. Equipment: the Simulator

A simulator, designed and constructed in CIOP-PIB's Department of Ergonomics, was used to perform measurements [9] (Figure 1). The simulator was equipped with a typical operator's seat and an industrial robot situated on a podium with a rigid foundation. A column with a horizontal extension arm was mounted in the rear. A monitor was fixed to the front part of the column, in a way that ensured its proper positioning according to operators' individual needs. A folding shield could be translated along the extension arm; it isolated operators from external influences [9].

The robot's positions were controlled with an acutator (spatial parameters: three linear

Figure 1. The simulator constructed at Poland's Central Institute for Labour Protection – National Research Institute (CIOP-PIB) (side view).

co-ordinates: x, y and z, and two angular co-ordinates), which was programmed through the position of a screen cursor. In some cases the operator enforced additional operations, such as change in the length of the arm of the hand lever.

In the test, the subject executed a tracking task by following a randomly generated line with a cursor by activating the tested actuator. Series of tests included control devices such as hand lever, pedal, steering wheel, hand wheel, and the number of parameters of the regulation system could be changed (see Słowikowski [1, 9] for details).

2.3. Characteristics of the Auditory Signal

A sound card was installed in the regulation system. It generated auditory signals corresponding to the regulation deviation according to the values presented in this section.

The frequency of the generated signal can be represented as follows:

$$f = f_0 \bullet 2^{x_t(\%)\frac{A_n}{1200}}, \quad (5)$$

where f_0 = 110 Hz, and the coefficient of A_n = 1200 corresponds to the doubling of frequency f_0 for instantaneous value of deviation x_t =1. The A_n values are as follows: A_1: 50, A_2: 75, A_3: 100, A_4: 150, A_5: 200, A_6: 300.

3. TESTS

3.1. Variable Parameters of the Experiment

The experiment was conducted when

- the maximum quality of regulation appeared within the assumed ranges of parameter variation,
- changes in the quality of regulation were clearly detectable,
- the measurement error did not exceed 0.5%.

Prior to the main experiment pilot tests were conducted. The parameters of the final experiments are presented in Figure 2.

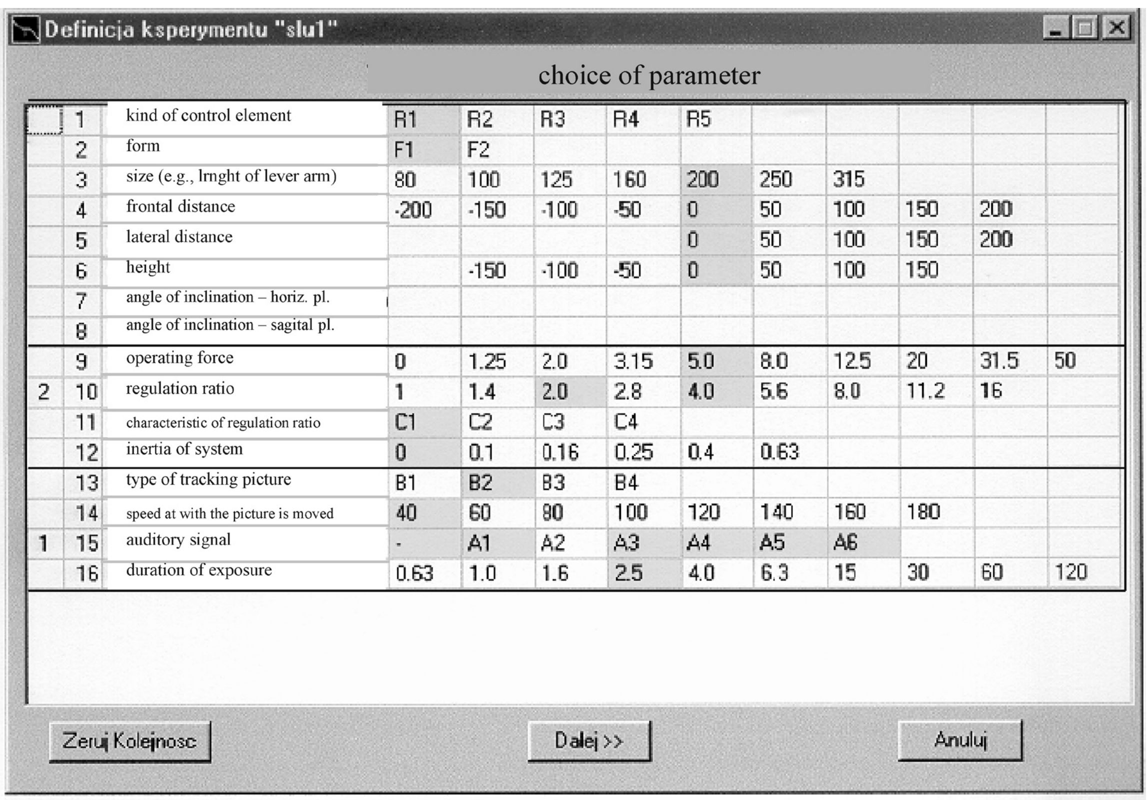
The actuator was a hand lever with a spherical handle. Arm length L = 200 mm was constant. A previous test of the quality of regulation showed this length was found optimal at quasi-zero loading [9]. Optimal frontal and lateral distances, and handle height were adjusted individually for each subject participating in the test. The lever's axis of revolution was positioned in the horizontal plane, and oriented perpendicularly to the sagittal plane.

The force of 5 N was applied to the handle. This value was optimal in view of regulation quality. From a set of transmission ratios shown in Table 1, two values of regulation ratios were used. The low value of $i = 2$, corresponding to the handle shaft s of 104 mm, was selected based on the investigated regulation quality [9]. The higher value, $i = 4$, corresponded to a relatively short handle shaft of 52 mm and was selected taking into account the stress concentration associated with the regulation process. The regulation ratio was a constant imposing linear characteristic of regulation.

TABLE 1. Regulation Ratios for Different Handle Shafts

Handle shaft (mm)	200	144	104	76	52	36	28	20	12
Regulation ratio	1	1.4	2*	2.8	4*	5.6	8	11.2	16

Notes. *—values used in the experiment.



	1	kind of control element	R1	R2	R3	R4	R5					
	2	form	F1	F2								
	3	size (e.g., lrnght of lever arm)	80	100	125	160	200	250	315			
	4	frontal distance	-200	-150	-100	-50	0	50	100	150	200	
	5	lateral distance					0	50	100	150	200	
	6	height		-150	-100	-50	0	50	100	150		
	7	angle of inclination – horiz. pl.										
	8	angle of inclination – sagital pl.										
	9	operating force	0	1.25	2.0	3.15	5.0	8.0	12.5	20	31.5	50
2	10	regulation ratio	1	1.4	2.0	2.8	4.0	5.6	8.0	11.2	16	
	11	characteristic of regulation ratio	C1	C2	C3	C4						
	12	inertia of system	0	0.1	0.16	0.25	0.4	0.63				
	13	type of tracking picture	B1	B2	B3	B4						
	14	speed at with the picture is moved	40	60	80	100	120	140	160	180		
1	15	auditory signal	-	A1	A2	A3	A4	A5	A6			
	16	duration of exposure	0.63	1.0	1.6	2.5	4.0	6.3	15	30	60	120

Figure 2. Experimental window.

A standard tracked line was a random one of trapezoidal shape. The speed of horizontal travel of the tracked image was 40 mm/s. Follow-up tracking was supported with an auditory signal of variable frequency (see section 2.3). A single test lasted for 2.5 min (150 s).

3.2 Structure of a Single Experiment

Tests were conducted for each of regulation ratios 2 or 4 and six values of A_n. Thus the number of combinations of independent variable equalled $N = 2 \times 6 = 12$. The optimal combinations of parameters were selected in view of regulation quality Q.

The basic test cycle is shown in Figure 3. The test cycle was identical for each combination of regulation parameters. Cycle *a* included 8-s adaptation time to allow the subject to recognise the initial position of the cursor on the screen prior to the start of the follow-up process. The main measurement of regulation quality lasted for the time t_{ex} = 2.3 min. During the measurement period the deviation curve was integrated (Figure 4).

After the measurements new values of the parameters were set and the basic test cycle was repeated. The total measurement time per single test cycle was t_j = 2.7 min.

A test for one subject lasted T_{ob} = 48 min (Figure 5). The experiment started with about 10-min instruction given to the subject followed by about 5-min training during which the subject became familiar with the task and the range of regulation parameters, and learned how to perform the task. After the training, the subject was presented with a sequence of N basic test cycles. The duration of this phase of test was $T_N = N \bullet t_j$.

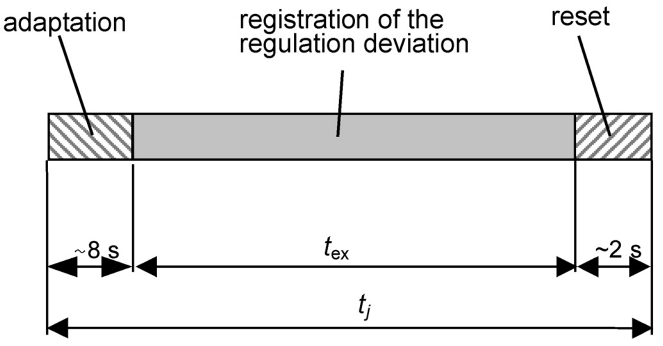


Figure 3. Structure of a basic test cycle. *Notes.* t_{ex}—phase of regulation quality registration, t_j—time of basic test cycle.

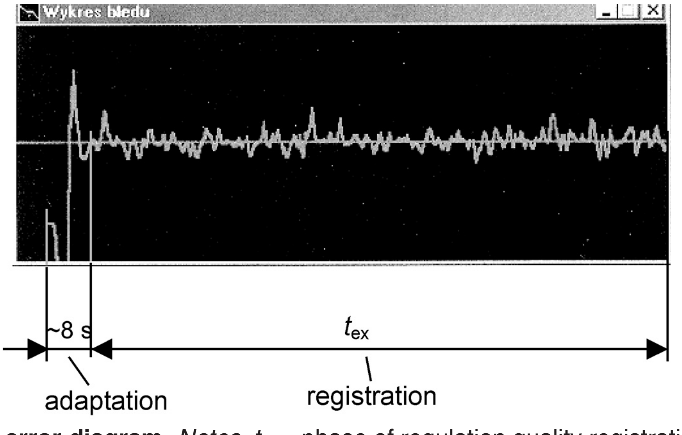


Figure 4. Regulation error diagram. *Notes.* t_{ex}—phase of regulation quality registration.

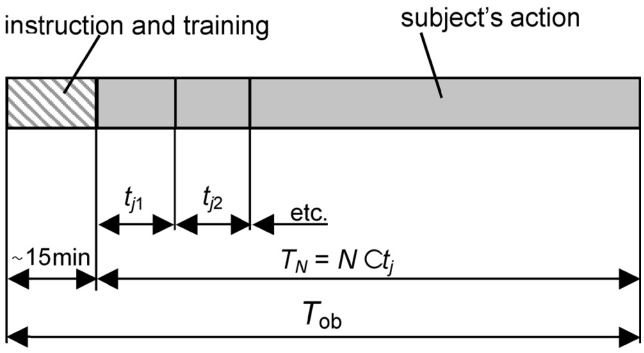


Figure 5. Overall structure of the experiment (for one subject). Notes. t_{j1}—first basic test cycle, t_{j2}—second basic test cycle, N—number of basic test cycles, T_N—duration of a sequence of N basic test cycles, T_{ob}—duration of test for one subject.

3.3. Training Phases

The applied regulation ratios are shown in column 1 of Table 2, while columns 2–7 represent the auditory signals used during this phase (column 2: no signal).

TABLE 2. Training Phases,

Regulation Ratio	A_0	A_1	A_3	A_4	A_5	A_6
2	phase 1	—	—	—	—	phase 4
4	phase 2	—	—	phase 3	—	—

Notes. A_0, A_1, A_3, A_4, A_5, A_6—values of auditory signal. The A_2 parameter was not used in the experiment.

The initial training phase provided familiarity with the regulation process and an optimal combination of parameters was selected. At the second stage of measurement higher regulation ratio was applied. At the third stage the regulation process of the second stage was repeated with an auditory signal added. The last, fourth, training step presents work at a lower regulation ratio, and the highest value of parameter A_n. Each subject had to be familiar with the extreme values of parameters to reduce stress and incidental emotional reactions, especially at the beginning of the test.

3.4. Subjects

Thirty three students of the Faculty of Automobile and Heavy Machinery Engineering of Warsaw University of Technology were tested. The subjects' average age was of 23.4 years (SD = 1.58). All subjects were in normal health as shown by periodical medical tests required for the students.

The subjects had normal hearing, which was checked with clinical audiometric tests. Accordingly to the requirements of the ISO 4869-1:1990 standard [12], hearing was understood to be normal when the hearing threshold was not higher than 15 dB for the frequency 2000 Hz and lower, and 25 dB for frequency above 2000 Hz.

3.5. Testing Conditions

Tests were performed in CIOP-PIB's Department of Ergonomics under natural daytime lighting, at room temperature, from 8:00 to 17:00 hours.

Environmental acoustic conditions were comparable to those typical for offices. Acoustic signals were presented to the subject through Sennheiser (Germany) H2270 headphones.

To reduce the influence of monotony and fatigue, the starting point of the experiment (given in Table 2) was different for each person.

4. RESULTS

4.1. The influence of the Auditory Signal on Regulation Quality

The results of these experiments were statistically analysed using the Statistica 6.0 package. In Student's *t* test over 51% of the results reached the significance level of $p \leq .05$, wheras over 62% reached the significance level of $p \leq .90$.

The average values of regulation deviation $\overline{U}$ are presented in Table 3. The minimal value $\overline{U}_{min} = 486$ was observed for the regulation ratio $i = 2$ and the parameter A_6. This value was used to calculate regulation quality Q according to Equation 4.

Regulation quality Q for each configuration of parameters is presented in Table 4. The maximum value of Q was observed for the regulation ratio $i = 2$ at the auditory level A_6. The minimum value of Q was observed with no auditory signal, both for $i = 2$ and $i = 4$. Therefore, the experiment proved that higher Q could be reached when the visual signal was supported with the auditory signal, proving the synergy between these two modes of perception.

In Figure 6, the course $Q = f(A)$ for $i = 2$ and $i = 4$ is presented in a logarithmic co-ordinate system. The horizontal lines labelled $i = 2$ and $i = 4$ represent Q with no auditory signal. Clearly, irrespective of the value of regulation ratio, supporting a visual signal with an auditory

TABLE 3. Average Values of Regulation Error $\bar{U}$

	Regulation Error $\bar{U}$					
Regulation Ratio	A_0	A_1	A_3	A_4	A_5	A_6
2	524	508	499	493	492	486*
4	542	511	515	518	497	505

Notes. A_0, A_1, A_3, A_4, A_5, A_6—values of auditory signal. The A_2 parameter was not used in the experiment. *—minimum value of $\bar{U}$.

TABLE 4. Regulation Quality Q for Each Configuration of Variable Parameters

	Regulation Quality Q					
Regulation Ratio	A_0	A_1	A_3	A_4	A_5	A_6
2	.927	.957	.974	.986	.988	1*
4	.897	.951	.944	.938	.978	.962

Notes. A_0, A_1, A_3, A_4, A_5, A_6—values of auditory signal. The A_2 parameter was not used in the experiment. *—maximum value of Q.

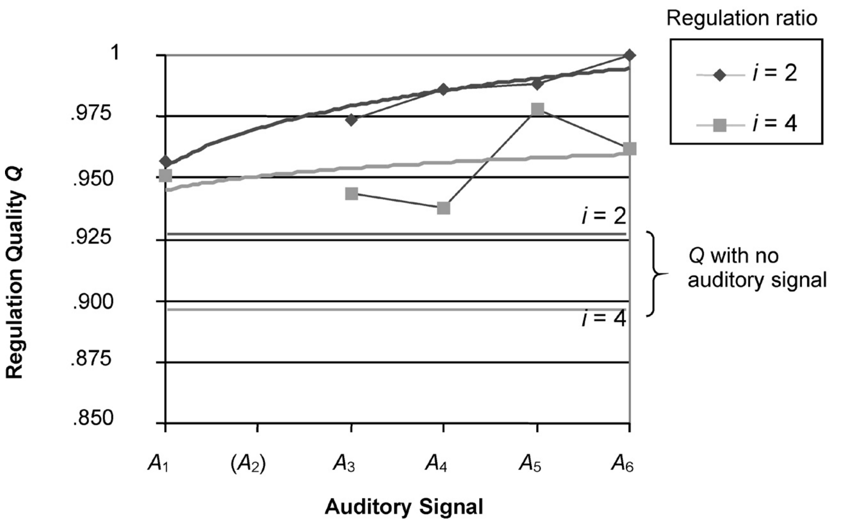


Figure 6. Regulation quality versus system transmission ratio and parameters of the auditory signal.

one results in an improvement in the quality of regulation. The results proved that the presence of additional auditory signal significantly influenced the regulation process. Within the range tested in this study, results were not influenced by the specific values of the parameters of the auditory signal.

4.2. The Influence of Synergy

To make the influence of synergy clearly visible, a comparison was made between the values of regulation quality for regulation with and without the support and averaged for different auditory signals (Table 5 and Figure 7). The bars shown in Figure 7 represent the regulation quality obtained, respectively, with and without the support of auditory signal at different regulation ratios. On average, there was over 5% of improvement in regulation quality for both auditory signals.

TABLE 5. Regulation Quality *Q* for a Visual Signal With and Without the Support of an Auditory Signal

	Regulation Quality *Q*	
Regulation Ratio	Visual + Auditory Signals	Visual Signal
2	.981	.927
4	.955	.897

5. CONCLUSIONS

The following conclusions can be drawn.

- There is synergy between visual and auditory cues in a follow-up regulation process.
- Supporting a visual deviation signal with an auditory one improves regulation quality by 5–6%.

The results may be useful in designing tele- and servo-mechanism regulation systems, especially remote ones, for heavy machinery and inspection robots controlled by operators with follow-up regulation systems.

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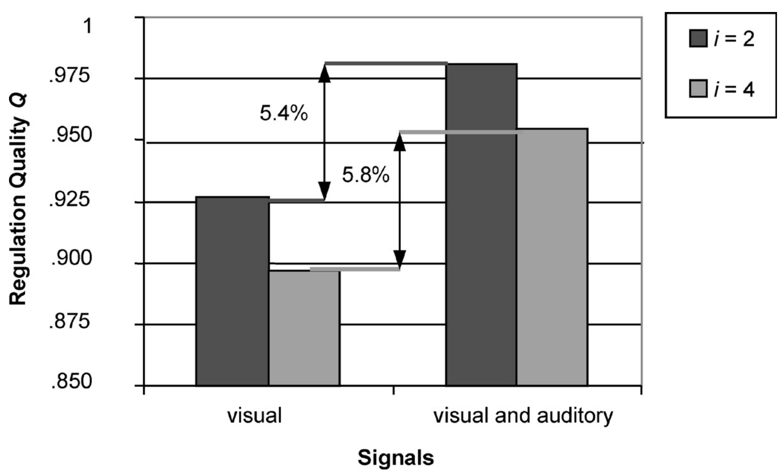

Figure 7. The influence of the synergy of visual and auditory signals on the regulation quality of control.

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