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Developing Visual Complexity Metrics for Automotive Human-Machine Interfaces

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Objective: The purpose of this study is to develop visual complexity metrics based on theoretical bases.

Background: With the development of IT technologies, drivers process a large amount of information caused by automotive human-machine interface (HMI), such as a cluster, a head-up display, and a center-fascia. In other words, these systems are becoming more complex and dynamic than traditional driving systems. Especially, these changes can lead to the increase of visual demands. Thus, a concept and tool is required to evaluate the complicated systems.

Method: We reviewed prior studies in order to analyze the visual complexity. Based on complexity studies and human perceptual characteristics, the dimensions characterizing the visual complexity were determined and defined.

Results: Based on a framework and complexity dimensions, a set of metrics for quantifying the visual complexity was developed.

Conclusion: We suggest metrics in terms of perceived visual complexity that can evaluate the in-vehicle displays.

Application: This study can provide the theoretical bases in order to evaluate complicated systems. In addition, it can quantitatively measure the visual complexity of In-vehicle information system and be helpful to design in terms of preventing risks, such as human error and distraction.

Keywords: In-vehicle Information system (IVIS), Perceived Visual Complexity (PVC), Human visual perception, Human-machine Interface, Instrument cluster

1. Introduction

The development of IT technologies contributes to the advent of smart vehicles, such as In-vehicle information system (IVIS). The system provides the visual information of various types: driving assistance information and comfort & entertainment information. Drivers can use these systems while driving, which the amount of information that they process is increasing. Several studies found that using the IVIS leads to driver distraction (Bengtsson, Grane, and Isaksson, 2003; Burnett and Porter, 2001). Governors Highway Safety Association (2011) classified the four types of driver distraction (visual, auditory, manual and cognitive distraction). The association confirmed the negative effects of the distractions by distractions by experimental

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studies. Especially, because drivers received at least 90% of the information through visual sense (Castro, 2008), it should be investigated in terms of how humans perceive visually complex information.

These changes in the driving environment could be more harmful to particular population, such as elderly drivers. Dingus et al. (1997) found that older drivers undergo difficulties in driving and using the information system simultaneously. Thus, they may be vulnerable to using state-of-the-art technology, such as IVIS, due to the increased visual information and their declined cognitive abilities.

Prior studies focused on the task-centered approach, such as the risk of call during driving and the danger of using the IVIS while driving (Dressel and Atchley, 2008; Maciej and Vollrath, 2009). However, these studies investigating the effect between only some variables can not examine the effect on the overall visual complexity of the system in driving situations, because the visual complexity is caused by many variables and their complicated interactions. Thus, theoretical bases and an evaluation framework with an integrated perspective are required to evaluate complicated systems.

The purpose of this study is to develop the visual complexity metrics based on theoretical bases. In section 2, we reviewed on complexity studies and human perception theories in terms of visual information. According to the review on prior researches, we suggested a framework for developing the visual Complexity metrics and a set of metrics for evaluating the visual complexity in section 3. Lastly, we discussed the results based on the theoretical bases.

2. Related Study

2.1 Visual complexity

Complexity generally refers to the difficulties of understanding a phenomenon in an environment. Complexity originated in a word of Latin language "complexus" that means "twist together". In order to have complexity, more than two components are needed and these are dependent (Heylighen, 1999). In the field of HMI, complexity definition are defined as three dimensions: **Quantity** of basic information elements in a system, **variety** of elements and **relations** between elements (Xing, 2005; 2007; Cummings et al., 2010).

Complexity is dependent in terms of human perception (Cummings et al., 2010; Ham et al., 2011; Xing, 2007). Humans perceive the visual complexity based on the objective characteristics of systems or objects. However, an observer has a unique thought about something, such as a certain phenomenon, a situation and an event (Cummings et al., 2010). Thus, some people may feel complicated about an object, but other people may feel simple about the object.

Henneman and Rouse (1986) classified the complexity into non-behavioral complexity and behavioral complexity. The non-behavioral complexity mainly includes the complexity respecting system conditions. The most of complexity studies, such as computational complexity, software complexity, physical system complexity, redundancy complexity, and the subjective nature of complexity, applied the concept of non-behavioral complexity. The latter includes the complexity concerning human's psychological-behavioral characteristics. More specifically, behavioral complexity is consisted of perceptual complexity and problem-solving complexity.

In the field of HMI, researchers use the complexity concept in order to not only understand human interaction with a system but also evaluate the design quality. Tullis (1983) suggested four characteristics that related to how operators effectively perceive information from a display. The characteristics are overall density (a percentage of the total character spaces available), local density (The number of filled character spaces near each character), grouping (The extent to which items form well-defined

perceptual groups) and layout display (the extent to which the arrangement of items on the frame). Because these characteristics are related to human perception, the complexity may be influenced by these factors.

Reinecke et al. (2013) investigated the relationship between perceived visual complexity (PVC) and colorfulness in order to predict the first impressions of user in terms of website aesthetics. They developed computational models to evaluate the PVC and colorfulness of website scenes. The suggested image metrics that related to color, space, and structure can be helpful to develop a measurement index for an in-vehicle display.

Meanwhile, Xing (2004; 2005; 2007; 2008) suggested a complexity measurement in order to evaluate Air Traffic Control (ATC). Based on the three-stage information processing (perception, cognition, action) and three complexity dimensions (Quantity, Variety, Relation), the measurement consists of a 3×3 matrix. The author identified some visual factors in terms of complexity caused by a system, and developed metrics and questionnaires. From a perceptual complexity approach, Xing (2007) suggested the metrics of information complexity for ATC displays, which are "number of fixation groups, variety of visual feature, and degree of clutter". However, it is ambiguous to measure the displays, because each metric is not clearly defined.

Cummings et al. (2010) suggested a Supervisory-control-complexity chain in order to evaluate the complexity of Nuclear Power Plant (NPP), i.e. environmental complexity, organizational complexity, interface complexity, and cognitive complexity. They categorized the complexity factors into two dimensions: quantity and variety. They suggested the interface complexity factors: "Information amount, Number of icons, Text to graphic ratio, and variety of colors". In the study, the degree of complexity is drawn by questionnaires and factors in terms of each corresponding complexity chain. However, there are limits that did not define the factors and did not provide how to measure these.

2.2 The Human perception of visual information

In order to consider the behavioral aspects such as visual perception or visual searching, we reviewed three represented theories on human perception that relate to how users perceive visual information. First, the information processing theory provides a conceptual structure in terms of how humans process information. Second, the visual feature integration theory dealt with operator's perception about visual objects having visual features. Finally, the perceptual organization theory provided a cognitive grouping mechanism about multiple visual objects.

According to Wickens (2002)'s information processing theory, humans conduct several steps to process the information. In other words, humans process the information through the perceptual process, i.e. environmental stimulus, attended stimulus, stimulus on the receptors, transduction, transmission, processing, perception, recognition, and action (Goldstein, 2013). Because working memory has limited capacity, the amount of information that they process is limited. The characteristic is also applied to complexity study. For example, increasing amount of information leads to increasing complexity in terms of performance (Kemps, 1999). In order to develop the complexity metrics in terms of using visual displays, Xing (2007) applied the information-processing theory as a simplified form: perception, cognition, and action.

The visual feature integration theory explains how humans perceive an object having visual features. According to Treisman and Gelade (1980), humans perceive an object through two stages. First stage is pre-attentive. In this stage, humans automatically perceive some visual features (shape, color, and orientation). In focused attention stage, humans perceive an object based on integration among features after pre-attentive stage.

The perceptual organization includes the principles that related to how humans perceive each object into the grouped object. According to the theory, humans perceive not individual objects but the single object through grouping laws. The representative

studies are gestalts laws (Wertheimer, 1923) and three grouping principles (Palmer, 1999). Table 1 and Table 2 show the perceptual organization principles.

Table 1. The gestalt's perceptual organization

Law	Description
Pragnanz	The pattern of visual information is seen into the simplified form.
Similarity	Similar objects appear to be grouped together.
Proximity	Adjacent objects appear to be grouped together.
Common fate	The movement of objects that are same orientation is perceived as a group.

Table 2. The grouping principles

Law	Description
Common region	The objects within the same region are seen as belonging together.
Uniform connectedness	A region that is connected into uniform visual features is perceived as a group.
Synchrony	Objects that appear at the same time are seen as a group.

3. A Framework for Developing the Visual Complexity Metrics

The basic idea of a framework is to predict visual complexity through a quantitative evaluation for individual visual objects used in order to present information in display. According to xing's the simplified form of information processing, we mainly consider perception (acquiring the visual features) and cognition (integrating the information based on incoming data) stages in order to develop the metrics for quantifying the visual information.

A conceptual diagram for visual complexity is represented in Figure 1. According to perception theories, we can take account of a minimum unit (which is a character, a figure, and an icon), visual features (which are color, shape, and size), and grouping criterions (which regular, orderly, and symmetric). Thus, in order to develop visual complexity metrics, we determined and defined three units of analysis (Table 3).

Based on perspectives of prior studies (Xing, 2004; 2005; 2007; Cummings et al., 2010), the dimensions characterizing the complexity of a visual scene were determined. Individual objects that compose the visual scene have relevance to dimensions, such as quantity, variety, relation. According to conditions of the dimensions, drivers may differently perceive the visual complexity because these dimensions influence the perceptual information processing.

3.1 Dimensions of visual complexity

We determined visual complexity dimensions based on the related studies in HMI field. The dimensions is quantity, variety, and relation. Cummings et al. (2010) determined dimensions which are size (of parts), variety (of parts), and rules/interconnections (between parts). Xing (2004; 2005; 2007) suggested three dimensions: quantity, variety and relation.

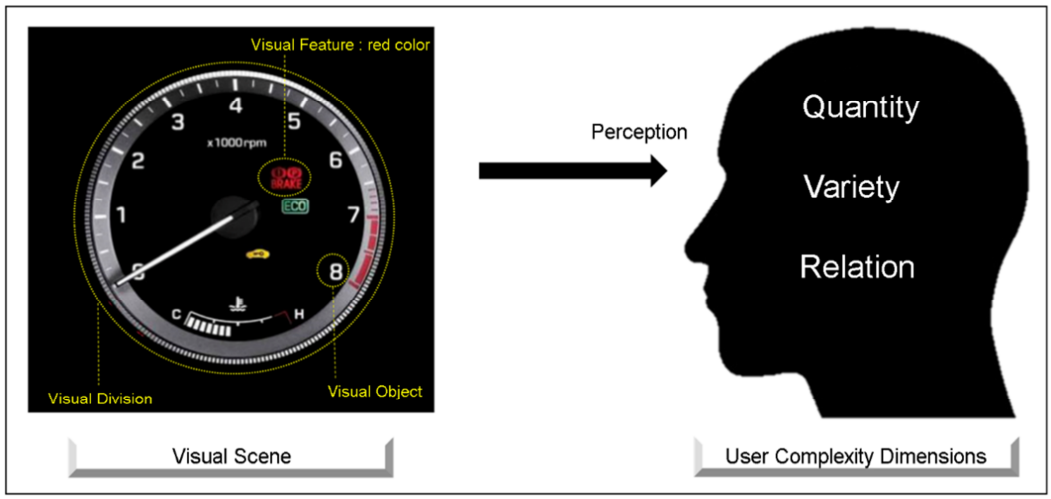

Figure 1. A conceptual diagram for visual complexity

Table 3. Three units of analysis in terms of visual scene

Unit of analysis	Description
Visual object	A minimum visual unit ex) characters, figures, and icon
Visual feature	The visual characteristics of units ex) color, shape
Visual division	Perceptually organized information area which composed of the individual units

Quantity is the number of basic information elements that exist in a system. Generally, the quantitative increase means increasing the number of individual objects within a system and it leads to increasing interaction possibility among components. The more the number of information increases, the more relations among the components are complicated. The difference of complexity degree in terms of the quantity is represented in Figure 2. The right image is more complicated relationships than the left image in terms of the quantity. Therefore, we defined the quantity as the number of visual units in a display. For example, the number of texts, icons, and indicators is quantitative measurements. Xing (2007) suggested the quantity measurements, such as "number of fixation groups and number of functional units". According to related study (Xing, 2004; Kemp, 1999), there are a positive relationship between the quantity and the visual complexity.

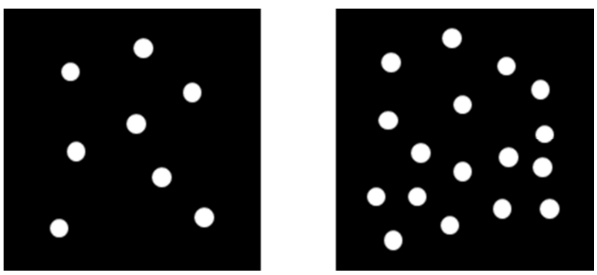

Figure 2. Images with increasing quantity from left to right

Variety means discrete characteristics between parts. The increase of variety in visual stimulus can make relation among components more complex (Heylighen, 1999; Oliva et al., 2004). If the number of parts within each system is same and the variety is different, drivers could differently perceive the complexity due to the discrete features of a system. The difference of complexity degree in terms of variety is represented in Figure 3. The right image is more complicated relationships than the left image in terms of the variety. Therefore, we defined the variety as the different visual features in terms of individual information in a display. Xing (2007) suggested the variety measurements, such as "background color, component color, shape, and size".

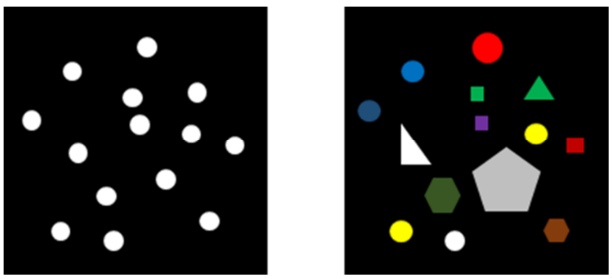

Figure 3. Images with increasing variety from left to right

Relation is interconnections between components in a system. The quantity and the variety are the complexity factors derived from the characteristics of individual parts. However, the relation is the complexity factor representing the structural aspect of a visual scene. In this study, we defined the relation as the interconnected characteristics of units. Xing (2007) suggested the relation measurements, such as "degree of clutter, relational complexity, and number of action cost". Kemp (1999) found that the matrix form is better than the random form for recall. The results indicated that the degree of structure could reduce complexity (e.g. Figure 4). In addition, Edmonds (1995) suggested that complexity is posited as a mid-point between order and disorder. Therefore, according to the degree of relational characteristics, there are a positive or a negative relationship between the relation and the PVC.

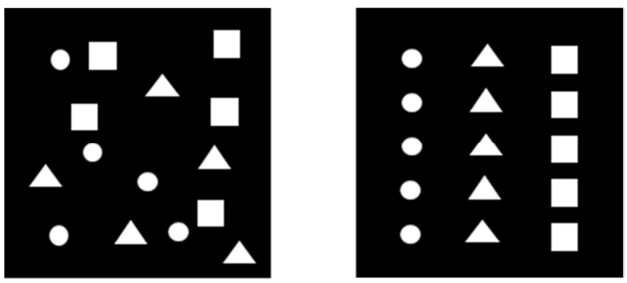

Figure 4. Images with increasing relation from left to right

3.2 Metrics for perceived visual complexity

The related study suggested various metrics based on the similar dimensions: Quantity (Cummings et al., 2010; Xing, 2007; Kemp, 1999), Variety (Cummings et al., 2010; Xing, 2007), and Relation (Xing, 2007; Kemps, 1999; Reinecke et al., 2013; Tullis, 1983).

The visual complexity is explained as three dimensions: quantity, variety, and relation. Meanwhile, a visual scene consists of two components, such as the visual object and the visual division. Each visual object has visual features: shape, color, and size. Lastly, considering the visual complexity dimensions and the units of analysis, we developed the set of metrics for quantifying the in-vehicle information display (Table 4). In addition, the metrics can be considered not only for analog displays but also for digital displays.

Table 4. The index of measuring visual complexity

Dimensions	Metrics	How to measure
Quantity	Amount of text information (ATI)	The total number of each alphanumerical character
	Amount of iconic information (AII)	The total number of each icon and symbols
	Amount of supplemental information (ASI)	The total number of scale figure
	Proportion of text information (PTI)	PTI = (Size of Text Information Area (STIA)) / (Size of Information Area (SIA))
	Proportion of iconic information (PII)	PII = (Size of Iconic Information Area (SIIA)) / (Size of Information Area (SIA))
	Proportion of supplemental information (PSI)	PSI = (Size of Supplemental Information Area (SSIA)) / (Size of Information Area (SIA))
	Percentage of blank space (PBS)	PBS = (SIA-STIA-SIIA-SSIA) / SIA)*100
Variety	No. of Unique visual shapes (UVS)	UVS = No. of Unique Visual Shapes
	Variety of shape size (VSS)	VSS = Variance of the size of each Unique Visual Shape (UVS)
	Overall color variety (OCV)	OCV = Total No. of Unique Color
	Background color variety (BCV)	BCV = Total No. of Unique Background Color
	Object color variety (OCV)	OCV = Total No. of Unique Object Color
	Colorfulness	A single questionnaire item
Relation	No. of visual divisions in a display	The total number of visual division
	Symmetricity	Two questionnaire items
	Level of alignment	The perpendicular and horizontal ordered degree of visual division
	Balancedness	Variance of the number of visual objects in each visual division

Quantity is the number of visual units. The quantity can be classified as amount and proportion (Cummings et al., 2010). The quantity metrics concerning amount includes characters, icons, symbols, and figures as countable variables in a display. Quantity metrics respecting proportion include characters, icons, figures, and black space as the occupied area of each variable.

Variety is the different visual features in terms of individual information in a display. The number of unique visual shapes (UVS) and the variety of shape size (VSS) are considered in order to measure different shapes in a display. The object color is mainly used in order to indicate information. The overall color is the total number of unique color used in a display (Cummings et al., 2010;

Xing, 2007). The colorfulness is one of the most notable features to invoke an emotional reaction (Reinecke et al., 2013) and is measured through a single questionnaire item of seven scales from not colorful to extremely colorful (Reinecke and Gajos, 2014; Hasler and Suesstrunk, 2003).

Relation is the interconnected characteristics of units. The number of visual division in a display is measured based on the concept of common region that is "the objects within the same region are seen as belonging together", such as information area inside the circles of Figure 5. The symmetricity is measured by the average of two items with rating scales, such as "The visual information has bilateral symmetry properly". "The group or structure of visual information is balanced" (Reinecke et al., 2013). The level of alignment is the perpendicular and horizontal ordered degree of visual division (Alemerien and Magel, 2014; Fu et al., 2007). The balancedness means variances of the number of visual objects in each visual division. The results are presented on Table 5 that is an example measuring an in-vehicle cluster.

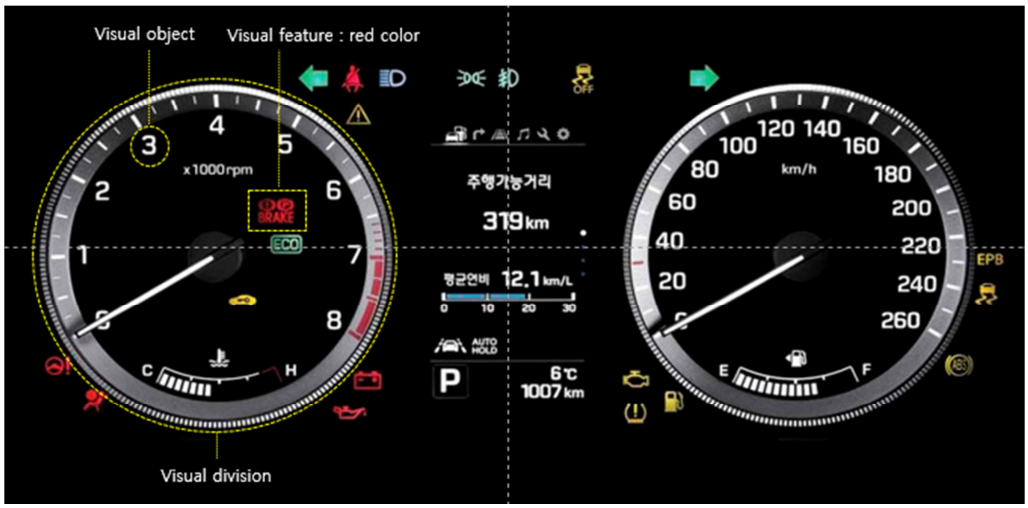

Figure 5. A sample cluster

Table 5. Measured value for a cluster

Metric	ATI	AII	ASI	PTI	PII	PSI	PBS	UVS	VSS
Measured value	127	40	96	14,144	15,640	6,354	0.56	1	0
Metric	OCV (overall)	BCV	OCV (object)	Colorfulness	Division	Symmetricity	Level of alignment	Balancedness	
Measured value	7	2	5	–	2	–	80	6.12	

4. Conclusion

The purpose of this study is to develop visual complexity metrics in terms of IVIS. Thus, we identified the complexity perspectives: the driver-oriented view and the system-oriented view. Based on the views, we reviewed related studies, such as the human

perception theories about visual information and the visual complexity studies. According to previous studies, the three units of analysis and the three dimensions were determined and defined. As a result, we suggested a framework for developing visual complexity metrics in order to evaluate IVIS.

The contribution of this study is that the theoretical bases can be provided for designers and developers in terms of evaluating a complicated system. Although Xing (2008) developed metrics of information complexity for ATC display, each metric is not clearly defined. Thus, it is ambiguous to measure a display. Similarly, Cummings (2010) did not define the factors and did not provide how to measure these. In this study, we provided how to measure a complicated visual system based on concrete definitions. In addition, Based a complexity approach, we explained the reason why human complicatedly perceived the system, such as IVIS. In summary, the degree of complexity is related to visual complexity dimensions (Heylighen, 1999; Kemp, 1999; Oliva et al., 2004; Xing, 2004).

From the pragmatic perspectives, the proposed metrics can be helpful to designing the visual systems. This study proposed the PVC approach for determining units of analysis and decomposing the visual systems into complexity metrics based on complexity and human perception. A set of metrics can be used to evaluate the visual complexity for a complicated system and the approach can be applied to other visual systems. In addition, designers and developers can make a comparison between systems based on quantitative criteria using the metrics.

The proposed metrics can quantitatively measure visual complexity for a system. In further study, in order to validate the metrics, we will collect many cluster images considering display types and the complexity levels of each dimension, and then measure the images. Moreover, we will investigate the relationship between visual complexity and performance, such as the effect of the complexity levels of each dimension on visual behavior using eye tracker. However, we need to consider evaluating how humans subjectively perceive the visual complexity in terms of complicated systems because complexity is dependent in terms of human perception. Then, it will be possible to investigate the PVC based on relationship between design factors and human factors.

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