TOSHIBA
Leading Innovation >>>

Bartenコントラスト感度関数モデルの空間速度拡張
A Spatio-Velocity Extension of Barten's CSF Model

佐々木 尚
東芝 セミコンダクター＆ストレージ社 (S&S社)

フラットパネルディスプレイの人間工学シンポジウム2012
社団法人 電子情報技術産業協会、ディスプレイデバイス事業委員会主催
2012/3/9

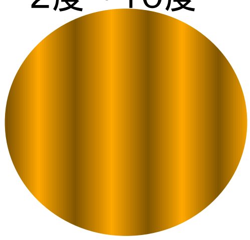
(VHF1-3, International Display Workshops 2011
2011/Dec/7 at Nagoya Convention Center, Japan.
で発表した内容)

© 2012 Toshiba Corporation

Contents

背景:コントラスト感度関数 (CSF) とは

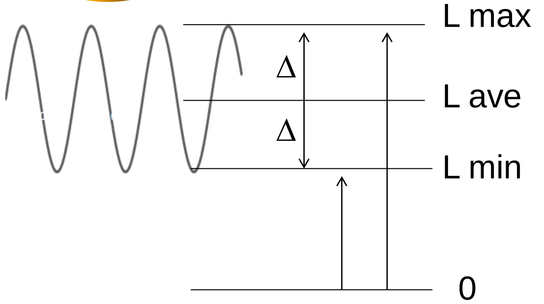
2度～10度



$\Delta = (L\,max - L\,min) / 2$

$L\,ave = (L\,max + L\,min) / 2$

CSF値 = L ave / Δ



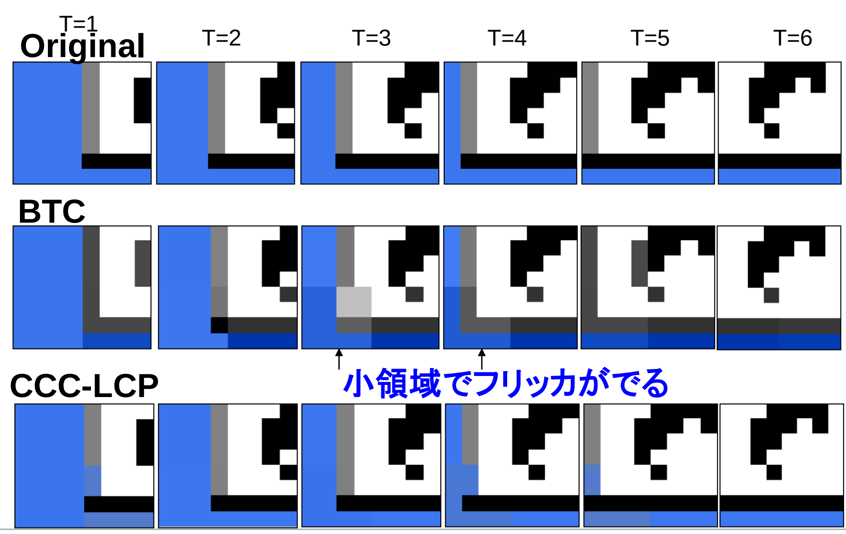
CSF値＝1
とは
真っ白　VS　真っ黒

© 2012 Toshiba Corporation

背景: 圧縮フリッカを考える

小領域
動き

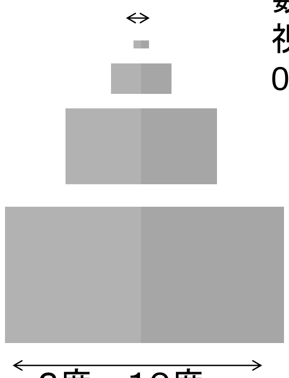
小領域、動き　に関するCSFが必要



© 2012 Toshiba Corporation

背景：コントラスト感度関数 (CSF) とは

小領域
数画素 ～
視距離3Hで
0.05 * (画素数) 度



2度～10度

大領域

動きに関しては大領域を対象としたCSFのみがある
Kelly & Daly SV-CSF,
Laird SV-CSF,
平井 SV-CSF

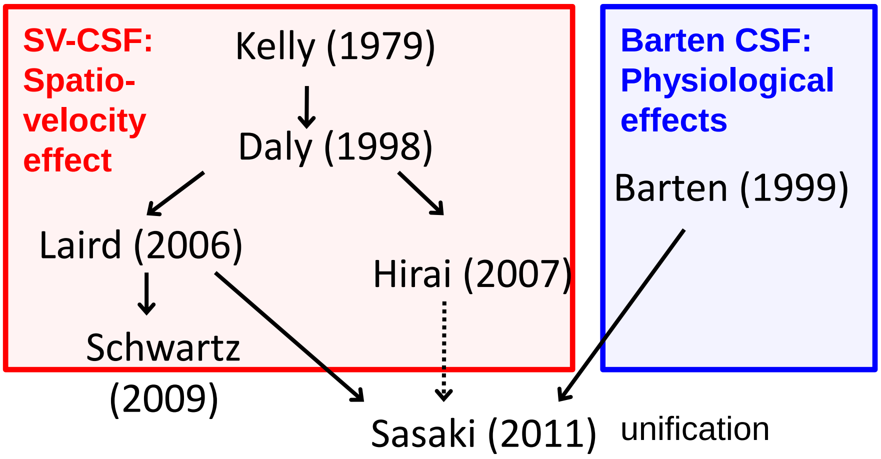
© 2012 Toshiba Corporation

Objective

- We will propose a new model on Spatio-Velocity Contrast Sensitivity Function (SV-CSF):
  - To evaluate image-processing algorithms such as block-wise memory-compression of LCD overdriving, artifact occurs in very small area. However, conventional SV-CSF model mainly targeted for large-area check of TV artifacts such as flickering and blurring. So, we need a new model.
- As a result, we will eventually have an unified treatment of two artifacts: flickering and blurring.
  - In this sense, unified treatment is a final objective.

© 2012 Toshiba Corporation

Historical Review of CSFs (Contrast Sensitivity Functions)



Problem: Each cannot treat both effects simultaneously.

The Barten CSF

$$CSF(u,w) = \frac{M_{opt}(u)/k}{\sqrt{\frac{2}{T}\left(\frac{1}{X_0^2}+\frac{1}{X_{max}^2}+\frac{1}{N_{max}^2}\right)\left(\frac{1}{\eta pE}+\frac{\Phi_0}{\left[H_1(w)\{1-H_2(w)F(u)\}\right]^2}\right)}}$$

u: spatial frequency
w: temporal frequency

$$M_{opt}(u) = e^{-2\pi^2\sigma^2u^2}$$

$$\sigma = \sqrt{\sigma_0^2 + (\sigma_{ab}d)^2}$$

$$E = \frac{\pi d^2}{4} L\left\{1-(d/9.7)^2+(d/12.4)^4\right\}$$

$$d = 5 - 3\tanh(0.4\log(L$$

$$\frac{\pi}{4}D^2 = X_o^2$$

確率50%で認識できるかどうかの閾値を与える等式

$$H_n(w) = \frac{1}{\left\{1+(2\pi w\tau_n)^2\right\}^{n/2}}$$

$$\tau_1 = \frac{\tau_{10}}{1+0.55\ln\left\{1+\left(1+\frac{D}{1}\right)^{0.6}\frac{E}{3.5}\right\}}$$

$$\tau_2 = \frac{\tau_{20}}{1+0.37\ln\left\{1+\left(1+\frac{D}{3.2}\right)^{5}\frac{E}{120}\right\}}$$

$$F(u) = 1-\sqrt{1-e^{-(u/u_0)^2}}$$

The Barten CSF

$$CSF(u,w)=\frac{M_{opt}(u)/k}{\sqrt{\frac{2}{T}\left(\frac{1}{X_0{}^2}+\frac{1}{X_{\max}{}^2}+\frac{1}{N_{\max}{}^2}\right)\left(\frac{1}{\eta pE}+\frac{\Phi_0}{\left[H_1(w)\{1-H_2(w)F(u)\}\right]^2}\right)}}$$

u: spatial frequency
w: temporal frequency

$$M_{opt}(u)=e^{-2\pi^2\sigma^2u^2}$$

$$\sigma=\sqrt{\sigma_0{}^2+(\sigma_{ab}d)^2}$$

$$E=\frac{\pi d^2}{4}L\{1-(d/9.7)^2+(d/12.4)^4\}$$

$$d=5-3\tanh(0.4\log(L))$$

$$\frac{\pi}{4}D^2=X_o{}^2$$

豊富な生理的なパラメータ

$$H_n(w)=\frac{1}{\{1+(2\pi w\tau_n)^2\}^{n/2}}$$

$$\tau_1=\frac{\tau_{10}}{1+0.55\ln\left\{1+\left(1+\frac{D}{1}\right)^{0.6}\frac{E}{3.5}\right\}}$$

$$\tau_2=\frac{\tau_{20}}{1+0.37\ln\left\{1+\left(1+\frac{D}{3.2}\right)^{5}\frac{E}{120}\right\}}$$

$$F(u)=1-\sqrt{1-e^{-(u/u_0)^2}}$$

The Hirai SV-CSF

$svCSF_{SHIFT}(u,v_R)$ * ~~$Cvd(DIS,v)$~~

$$svCSF_{SHIFT}(u,v_R)=k_{hirai}c_0c_1c_2v_R(c_1 2\pi u)^2\exp\left(-\frac{c_1 4\pi u}{u_{\max}}\right)$$

$$k_{hirai}=s_1+s_2\left|\log\left(c_2v_R/3\right)\right|^3$$

$$u_{\max}=\frac{p_1}{c_2v_R+2}$$

$$v_R=v+c_v$$

u: spatial frequency
v: spatio-velocity

空間速度 v がパラメータとしてある

Normalize SV-CSF by the value of v=0.

$$svCSF_{hirai}=\frac{svCSF(u,v_R)}{svCSF(u,v_R\mid(v=0))}$$

The Laird SV-CSF

$$svCSF(u, v_R) = k_{laird} c_0 c_1 c_2 v_R (c_1 2\pi u)^2 \exp\left(-\frac{c_1 4\pi u}{u_{\max}}\right)$$

$$k_{laird} = s_1 + s_2 \left|\log\left(\frac{c_2 v_R}{3}\right)\right|^3$$

$$u_{\max} = \frac{p_1}{c_2 v_R + 2}$$

$$v_R = |v - \min\{0.82 * v + 0.15, 80.0\}|$$

u: spatial frequency

v: spatio-velocity

Retinal velocity v_R is limited by 80 max.

Normalize SV-CSF by the value of v=0.

$$svCSF_{laird} = \frac{svCSF(u, v_R)}{svCSF(u, v_R \mid (v = 0))}$$

空間速度 v がパラメータとしてある

Three candidates as new SV-CSF

- **Exploit the Barten CSF as the primary body: CSF(u, w).**
- **Augment normalized SV-CSF as the modification factor.**

CSF1 = CSF(u, w) — Barten

CSF2 = CSF(u, w) * $svCSF_{hirai}$ — Hirai and Barten

CSF3 = CSF(u, w) * $svCSF_{laird}$ — Laird and Barten

豊富な生理的なパラメータ

空間速度 v がパラメータとしてある

Strategy for Candidate Selection

Experiment

- **Subjective experiments gather Detection Probabilities on Flickering.**

Theory

- **Proposed SV-CSFs predict CFF (Critical Flicker Frequency).**

Comparison

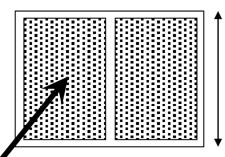
- **Compare predictions and experimental results to select the best candidate.**

© 2012 Toshiba Corporation

Experimental Setup

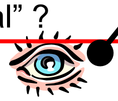
2AFC (Two-Alternative Forced Choice)

Randomly generate left and right images, then examinee is forced to choose exclusively one of response from the two: they are “different “ or “identical” ?



H=324mm

EIZO FlexSan S2100
60Hz, WXGA=1600x1200
Pixel pitch 0.270x0.270mm



Examinee Visual Acuity
0.8(20/25), 1.0(20/20).

MAX Luminance is 300 cd /m2
Viewing Distance 1H to 6H

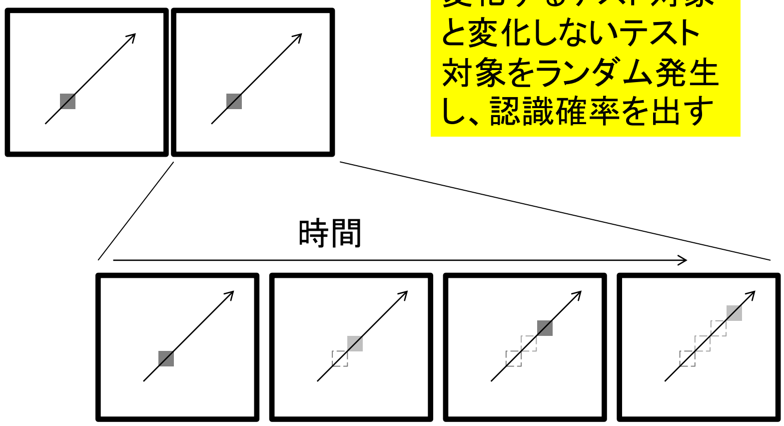
This test gathers detection probabilities.

© 2012 Toshiba Corporation

実験： テストの対象

左右の違いを検出できるか？

変化するテスト対象と変化しないテスト対象をランダム発生し、認識確率を出す

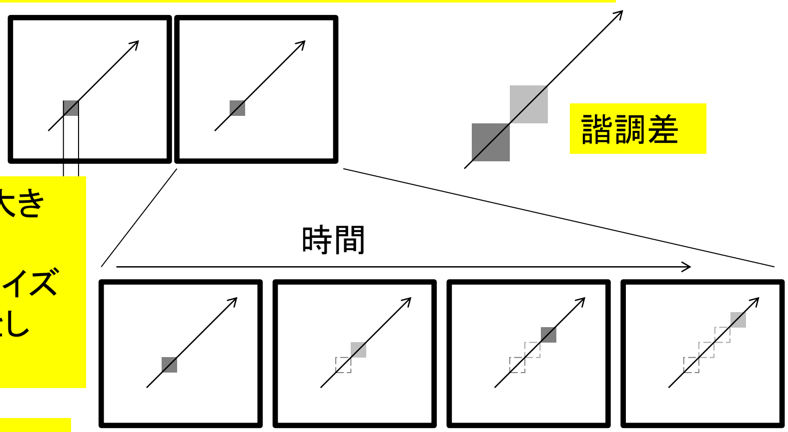


テスト対象は移動
諧調は時分割で変化

© 2012 Toshiba Corporation

実験： パラメータ

対象の移動速度 v ： 左上 1 [画素/フレーム]



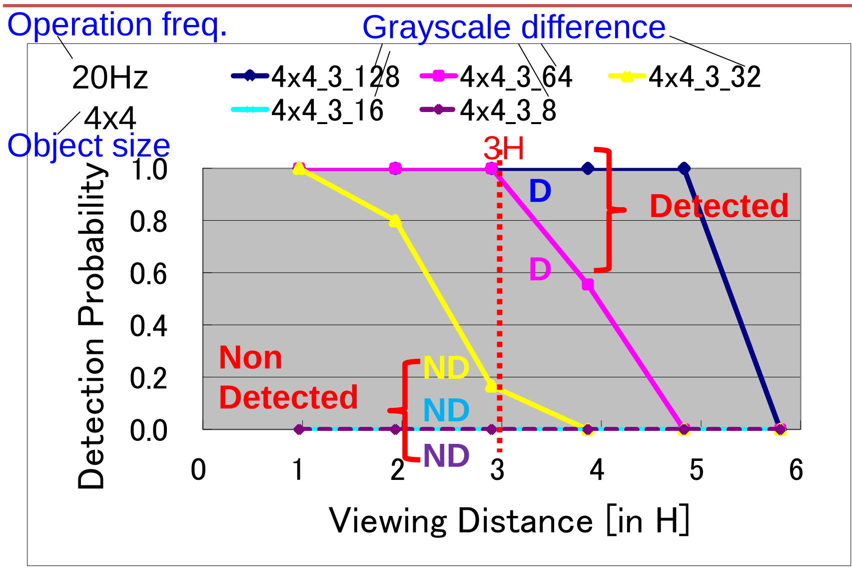
対象の大きさ：h
（画素サイズを単位として）

視距離
（1H～6H）

動作周波数： 30Hz, 20Hz, 15Hz

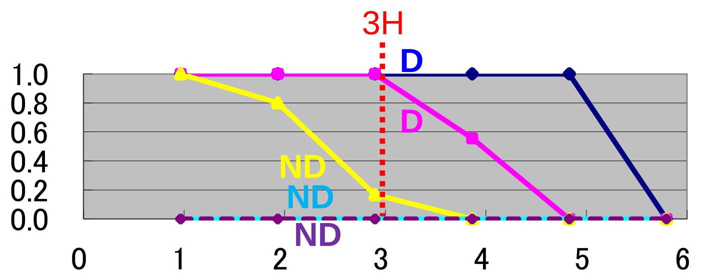
© 2012 Toshiba Corporation

Experimental Result Example



© 2012 Toshiba Corporation

Experimental Results Table



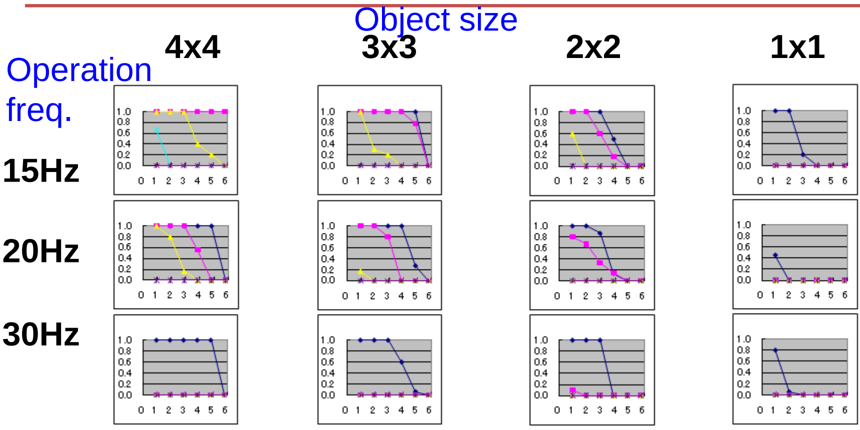
h=4 Difference → Frequency ↓	128	64	32	16
20Hz	D	D	ND	ND

© 2012 Toshiba Corporation

Experimental Results

Object size

Operation freq.



h=4 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	D	ND
20Hz	D	D	ND	ND
30Hz	D	ND	ND	ND

h=3 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	ND	ND
20Hz	D	50	ND	ND
30Hz	D	ND	ND	ND

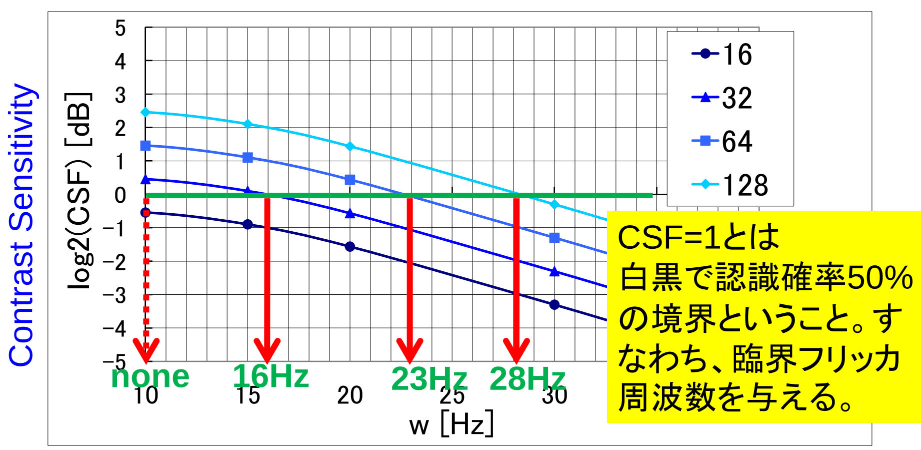
h=2 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	ND	ND
20Hz	D	30	ND	ND
30Hz	D	ND	ND	ND

h=1 Difference → Frequency ↓	128	64	32	16
15Hz	20	ND	ND	ND
20Hz	ND	ND	ND	ND
30Hz	ND	ND	ND	ND

© 2012 Toshiba Corporation

Theory: Prediction Procedure

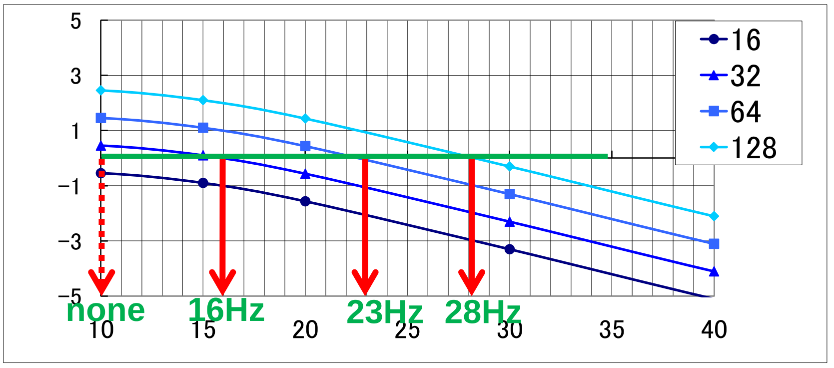
How to Predict CFF(Critical Flicker Frequency) by CSF



Temporal Frequency

© 2012 Toshiba Corporation

Theory: Predicted CFF



CFF [Hz] Difference → h ↓	128	64	32	16
h=4	28.0	23.0	16.0	None

© 2012 Toshiba Corporation

Theory: CFF Predictions

CSF candidate

Barten | Hirai + Barten | Laird + Barten

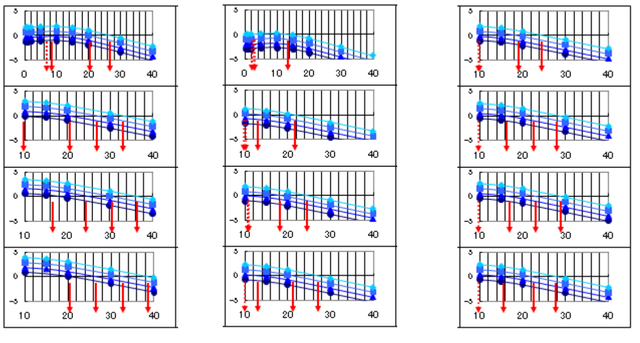
Object size

h=1

h=2

h=3

h=4



Barten:

CFF [Hz] Difference → h ↓	128	64	32	16
h=1	27	21	9	None
h=2	33	27	21	10
h=3	37	31	25	17
h=4	39	33	27	21

Hirai + Barten:

CFF [Hz] Difference → h ↓	128	64	32	16
h=1	14	None	None	None
h=2	22	13.5	None	None
h=3	25	18.5	None	None
h=4	27.5	22	13.5	None

Laird + Barten:

CFF [Hz] Difference → h ↓	128	64	32	16
h=1	25.0	19.5	None	None
h=2	28.5	23.0	16.5	None
h=3	29.3	23.5	17.5	None
h=4	28.0	23.0	16.0	None

© 2012 Toshiba Corporation

Comparison Procedure: Example

Experiments

h=4 Difference → Frequency ↓	128	64	32	16
30Hz	D	ND	ND	ND

Theory

CFF [Hz] Difference → h ↓	128	64	32	16
h=4	39	33	27	21

Operation freq. = 30 < 33 = CFF

D D ND ND

Comparison

h=4 Difference → Frequency ↓	128	64	32	16
30Hz	D	D	ND	ND

D disagreement

理論予測と実測の不一致

Comparison selects CSF3 (Laird and Barten)

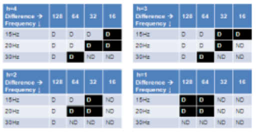
Experiments

h=1 Difference → Frequency ↓	128	64	32	16
15Hz	20	ND	ND	ND
20Hz	ND	ND	ND	ND
30Hz	ND	ND	ND	ND

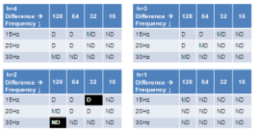
Theory

CFF [Hz] Difference → h ↓	128	64	32	16
h=1	25.0	19.5	None	None
h=2	28.5	23.0	16.5	None
h=3	29.3	23.5	17.5	None
h=4	28.0	23.0	16.0	None

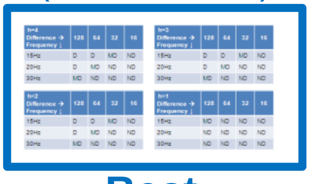
CSF1
(Barten)



CSF2
(Hirai + Barten)



CSF3
(Laird + Barten)



D **disagreement**

Best

The best CSF3 (Laird and Barten)

CSF3 = CSF(u, **w**) * svCSF$_{laird}$ (u, **v**)
w: flickering v: blurring

$$CSF(u,w) = \frac{M_{opt}(u)/k}{\sqrt{\frac{2}{T}\left(\frac{1}{X_0{}^2}+\frac{1}{X_{\max}{}^2}+\frac{1}{N_{\max}{}^2}\right)\left(\frac{1}{\eta pE}+\frac{\Phi_0}{[H_1(w)\{1-H_2(w)F(u)\}]^2}\right)}}$$

Barten CSF

$$svCSF_{laird} = \frac{svCSF(u,v_R)}{svCSF(u,v_R \mid (v=0))}$$

$$svCSF(u,v_R) = k_{laird}c_0c_1c_2v_R(c_1 2\pi u)^2 \exp\left(-\frac{c_1 4\pi u}{u_{\max}}\right)$$

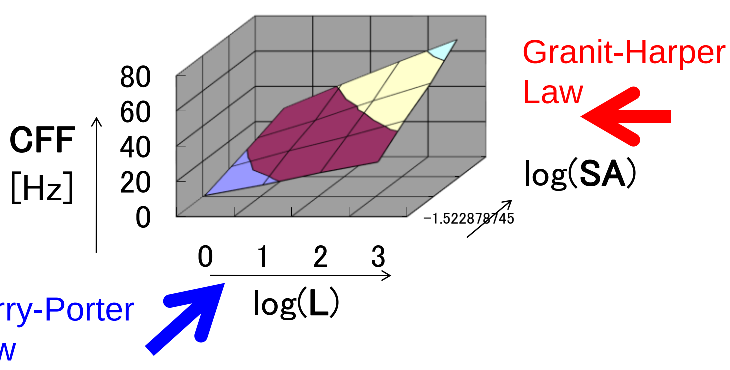
Laird SV-CSF

$$k_{laird} = s_1 + s_2\left|\log\left(\frac{c_2 v_R}{3}\right)\right|^3 \qquad u_{\max} = \frac{p_1}{c_2 v_R + 2}$$

$$v_R = \left|v - \min\{0.82 * v + 0.15, 80.0\}\right|$$

Discussion: a versatile applicability of CSF

The integrated Ferry-Porter Law and Granit-Harper Law.



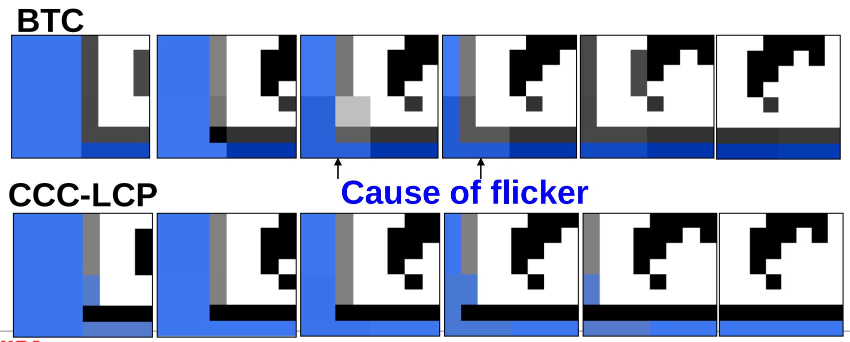
CFF=23.4+10.3 log(L) + 10.7 log(SA)
where L is a luminance, SA is subtending-angle.

Discussion: another application of CSF

Intuitive Design Guideline of Compression:
When SA is half, 1 bit is decreased.

$\log_2(C)$: bit depth

$$CFF = 29.0 + 4.06\log_2(L) + \mathbf{3.19\log_2(SA) - 3.05\log_2(C)}$$
$$+ 0.400\log_2(L)\log_2(SA) - 0.133\log_2(L)\log_2(C) + 0.0127\{\log_2(C)\}^2$$



Conclusions – as a first trial to the unification

- **The proposed SV-CSF treats both aspects – spatio-velocity effects and physiological parameters. So, a small-area artifact is treated.**
- **An unified foundation of two artifacts: flickering and blurring. That is, a phenomenon "Flickering is blurred" is formalized by the proposed SV-CSF.**

Future Directions

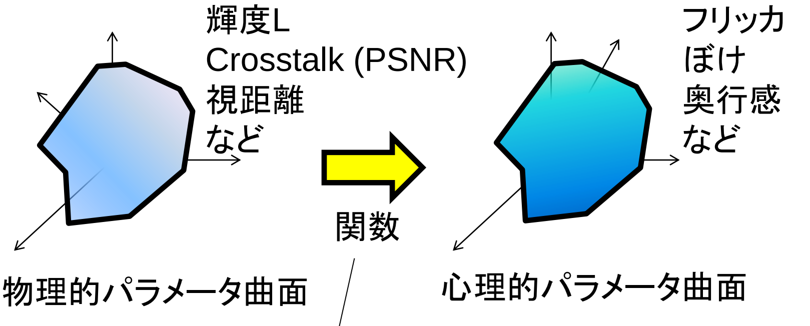
- Explicit & Simpler Expression for the Normalized CSF.

$$svCSF_{laird} = \frac{svCSF(u, v_R)}{svCSF(u, v_R \mid (v=0))}$$

- Chromatic SV-CSF.
- Scotopic/Mesopic CSF and SV-CSF.
- CFF macro models including other parameters such as bit depth, spatio-velocity, …
- SV-CSF for 3D viewing: introduce the parameter “angle of convergence”? Foreground / background moving speed? Background blur? etc

© 2012 Toshiba Corporation

IDW’11 3D8/VHF8-4 論文



「FPDの人間工学的な評価」とはこの関数のことである。

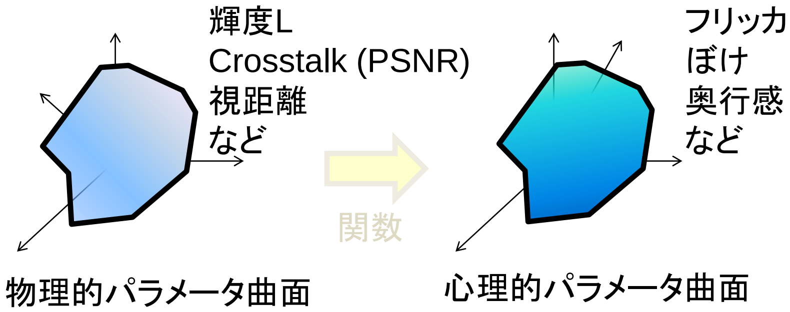
3D8/
VHF8 - 4

Ergonomic Assessment Theory for the Standardisation of 3D Displays

C. Kato[*,**], *S. Uehara*[*,***], *H. Ujike*[*,****], *Y. Hisatake*[*,*****]
[*] *Japanese Ergonomics Nat. Committee, Japan*
[**] *Hitachi, Japan*
[***] *Toshiba, Japan*
[****] *AIST, Japan*
[*****] *Toshiba Mobile Display, Japan*

© 2012 Toshiba Corporation

Future Directions – 提案「等式としてのCSF」

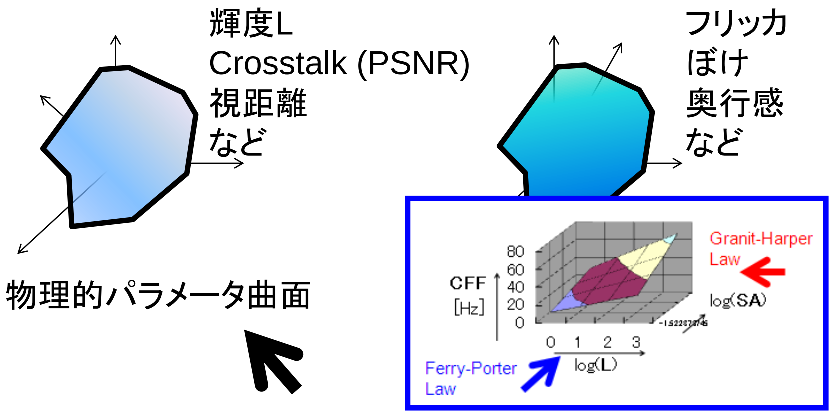


CSF(u, **w**) * svCSF$_{laird}$ (u, **v**)　の3D用改良

各種パラメータを結びつける「等式」＝「超曲面」

© 2012 Toshiba Corporation

Future Directions – 提案「等式としてのCSF」



CSF(u, **w**) * svCSF$_{laird}$ (u, **v**)　の3D用改良

各種パラメータを結びつける「等式」＝「超曲面」

© 2012 Toshiba Corporation

Thank you for your kind attention.

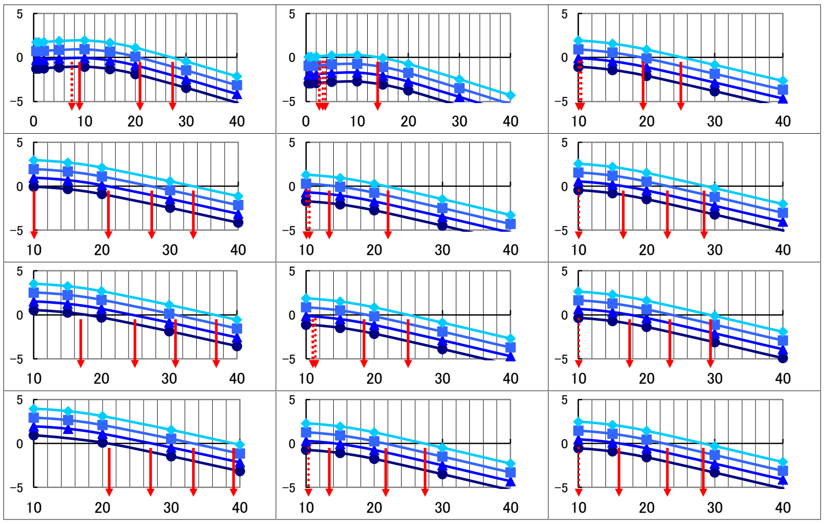
TOSHIBA
Leading Innovation

補足資料

© 2012 Toshiba Corporation

CFF Prediction Matrix

	Barten	Hirai + Barten	Laird + Barten
h=1			
h=2			
h=3			
h=4			



© 2012 Toshiba Corporation

Predicted CFF Summary

None = no CFF

Barten

CFF [Hz] Difference → h ↓	128	64	32	16
h=1	27	21	9	None
h=2	33	27	21	10
h=3	37	31	25	17
h=4	39	33	27	21

Hirai + Barten

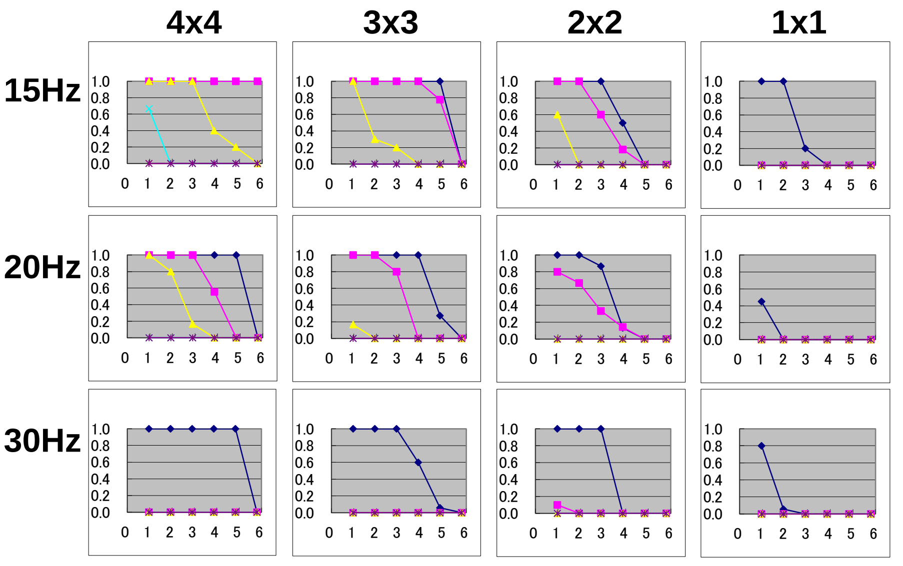
CFF [Hz] Difference → h ↓	128	64	32	16
h=1	14	None	None	None
h=2	22	13.5	None	None
h=3	25	18.5	None	None
h=4	27.5	22	13.5	None

Laird + Barten

CFF [Hz] Difference → h ↓	128	64	32	16
h=1	25.0	19.5	None	None
h=2	28.5	23.0	16.5	None
h=3	29.3	23.5	17.5	None
h=4	28.0	23.0	16.0	None

© 2012 Toshiba Corporation

Experimental Results Matrix



© 2012 Toshiba Corporation

Experimental Results Summary

h=4 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	D	ND
20Hz	D	D	ND	ND
30Hz	D	ND	ND	ND

h=3 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	ND	ND
20Hz	D	50	ND	ND
30Hz	D	ND	ND	ND

h=2 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	ND	ND
20Hz	D	30	ND	ND
30Hz	D	ND	ND	ND

h=1 Difference → Frequency ↓	128	64	32	16
15Hz	20	ND	ND	ND
20Hz	ND	ND	ND	ND
30Hz	ND	ND	ND	ND

D=detected, ND=non-detected, number is a detection percent.

3H Viewing Distance

© 2012 Toshiba Corporation

Comparison by CSF1 (genuine Barten)

h=4 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	D	**D**
20Hz	D	D	**D**	**D**
30Hz	D	**D**	ND	ND

h=3 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	**D**	**D**
20Hz	D	D	**D**	ND
30Hz	D	**D**	ND	ND

h=2 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	**D**	ND
20Hz	D	**D**	**D**	ND
30Hz	D	ND	ND	ND

h=1 Difference → Frequency ↓	128	64	32	16
15Hz	**D**	**D**	ND	ND
20Hz	**D**	**D**	ND	ND
30Hz	ND	ND	ND	ND

D=detected, MD=marginally-detected, ND=non-detected

D disagreement

Comparison by CSF2 (Hirai and Barten)

h=4 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	MD	ND
20Hz	D	D	ND	ND
30Hz	MD	ND	ND	ND

h=3 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	MD	ND
20Hz	D	MD	ND	ND
30Hz	MD	ND	ND	ND

h=2 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	**D**	ND
20Hz	MD	D	D	ND
30Hz	**ND**	ND	ND	ND

h=1 Difference → Frequency ↓	128	64	32	16
15Hz	MD	ND	ND	ND
20Hz	ND	ND	ND	ND
30Hz	ND	ND	ND	ND

D=detected, MD=marginally-detected, ND=non-detected

D disagreement

Comparison by CSF3 (Laird and Barten)

h=4 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	MD	ND
20Hz	D	MD	ND	ND
30Hz	MD	ND	ND	ND

h=3 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	MD	ND
20Hz	D	MD	ND	ND
30Hz	MD	ND	ND	ND

h=2 Difference → Frequency ↓	128	64	32	16
15Hz	D	D	MD	ND
20Hz	D	MD	ND	ND
30Hz	MD	ND	ND	ND

h=1 Difference → Frequency ↓	128	64	32	16
15Hz	MD	ND	ND	ND
20Hz	ND	ND	ND	ND
30Hz	ND	ND	ND	ND

D=detected, MD=marginally-detected, ND=non-detected

D disagreement

© 2012 Toshiba Corporation