SOME NEW INEQUALITIES FOR HERMITE-HADAMARD DIVERGENCE IN INFORMATION THEORY

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Abstract. In this paper we prove some new inequalities for Hermite-Hadamard divergence in Information Theory.

1. Introduction

One of the important issues in many applications of Probability Theory is finding an appropriate measure of *distance* (or *difference* or *discrimination*) between two probability distributions. A number of divergence measures for this purpose have been proposed and extensively studied by Jeffreys [1], Kullback and Leibler [2], Rényi [3], Havrda and Charvat [4], Kapur [5], Sharma and Mittal [6], Burbea and Rao [7], Rao [8], Lin [9], Csiszár [10], Ali and Silvey [12], Vajda [13], Shioya and Da-te [40] and others (see for example [5] and the references therein).

These measures have been applied in a variety of fields such as: anthropology [8], genetics [14], finance, economics, and political science [15], [16], [17], biology [18], the analysis of contingency tables [19], approximation of probability distributions [20], [21], signal processing [22], [23] and pattern recognition [24], [25]. A number of these measures of distance are specific cases of f-divergence and so further exploration of this concept will have a flow on effect to other measures of distance and to areas in which they are applied.

Let the set χ and the $\sigma-$finite measure μ be given and consider the set of all probability densities on μ to be defined on $\Omega := \left\{p | p : \chi \to \mathbb{R},\, p(x) \geq 0,\, \int p(x)\, d\mu(x) = 1\right\}$. The Kullback-Leibler divergence [2] is well known among the χ information divergences. It is defined as:

$$D_{KL}(p,q) := \int_{\chi} p(x) \log\left[\frac{p(x)}{q(x)}\right] d\mu(x), \quad p,q \in \Omega, \tag{1.1}$$

where log is to base 2.

In Information Theory and Statistics, various divergences are applied in addition to the Kullback-Leibler divergence. These are the: *variation distance* D_v, *Hellinger distance* D_H [1], χ^2-*divergence* D_{χ^2}, $\alpha-$*divergence* D_α, *Bhattacharyya distance* D_B [2], *Harmonic distance* D_{Ha}, *Jeffreys distance* D_J [1], *triangular discrimination* D_Δ [35], etc... They are defined as follows:

$$D_v(p,q) := \int_{\chi} |p(x) - q(x)|\, d\mu(x), \quad p,q \in \Omega; \tag{1.2}$$

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$$D_H(p,q) := \int_\chi \left|\sqrt{p(x)} - \sqrt{q(x)}\right| d\mu(x), \quad p,q \in \Omega; \tag{1.3}$$

$$D_{\chi^2}(p,q) := \int_\chi p(x)\left[\left(\frac{q(x)}{p(x)}\right)^2 - 1\right] d\mu(x), \quad p,q \in \Omega; \tag{1.4}$$

$$D_\alpha(p,q) := \frac{4}{1-\alpha^2}\left[1 - \int_\chi [p(x)]^{\frac{1-\alpha}{2}} [q(x)]^{\frac{1+\alpha}{2}} d\mu(x)\right], \quad p,q \in \Omega; \tag{1.5}$$

$$D_B(p,q) := \int_\chi \sqrt{p(x)\,q(x)}\,d\mu(x), \quad p,q \in \Omega; \tag{1.6}$$

$$D_{Ha}(p,q) := \int_\chi \frac{2p(x)\,q(x)}{p(x)+q(x)} d\mu(x), \quad p,q \in \Omega; \tag{1.7}$$

$$D_J(p,q) := \int_\chi [p(x) - q(x)] \ln\left[\frac{p(x)}{q(x)}\right] d\mu(x), \quad p,q \in \Omega; \tag{1.8}$$

$$D_\Delta(p,q) := \int_\chi \frac{[p(x) - q(x)]^2}{p(x)+q(x)} d\mu(x), \quad p,q \in \Omega. \tag{1.9}$$

For other divergence measures, see the paper [5] by Kapur or the book on line [6] by Taneja. For a comprehensive collection of preprints available on line, see the RGMIA web site `http://rgmia.vu.edu.au/papersinfth.html`

Csiszár $f-$divergence is defined as follows [10]

$$D_f(p,q) := \int_\chi p(x)\, f\left[\frac{q(x)}{p(x)}\right] d\mu(x), \quad p,q \in \Omega, \tag{1.10}$$

where f is convex on $(0,\infty)$. It is assumed that $f(u)$ is zero and strictly convex at $u = 1$. By appropriately defining this convex function, various divergences are derived. All the above distances $(1.1)-(1.9)$, are particular instances of $f-$divergence. There are also many others that are not in this class (see for example [5] or [6]). For the basic properties of $f-$divergence see [7]-[10].

In [11], Lin and Wong (see also [9]) introduced the following divergence

$$D_{LW}(p,q) := \int_\chi p(x) \log\left[\frac{p(x)}{\frac{1}{2}p(x) + \frac{1}{2}q(x)}\right] d\mu(x), \quad p,q \in \Omega. \tag{1.11}$$

This can be represented as follows, using the Kullback-Leibler divergence:

$$D_{LW}(p,q) = D_{KL}\left(p, \frac{1}{2}p + \frac{1}{2}q\right).$$

Lin and Wong have established the following inequalities

$$D_{LW}(p,q) \le \frac{1}{2} D_{KL}(p,q); \tag{1.12}$$

$$D_{LW}(p,q) + D_{LW}(q,p) \le D_v(p,q) \le 2; \tag{1.13}$$

$$D_{LW}(p,q) \le 1. \tag{1.14}$$

In [45], Shioya and Da-te improved (1.12) – (1.14) by showing that

$$D_{LW}(p,q) \le \frac{1}{2} D_v(p,q) \le 1.$$

In the same paper [45], the authors introduced the generalised Lin-Wong $f-$divergence $D_f\left(p, \frac{1}{2}p + \frac{1}{2}q\right)$ and the Hermite-Hadamard (HH) divergence

$$D_{HH}^{f}(p,q) := \int_{\chi} p(x) \frac{\int_1^{\frac{q(x)}{p(x)}} f(t)\,dt}{\frac{q(x)}{p(x)} - 1} d\mu(x), \quad p,q \in \Omega \tag{1.15}$$

and, by use of the Hermite-Hadamard inequality for convex functions, proved the following basic inequality

$$D_f\left(p, \frac{1}{2}p + \frac{1}{2}q\right) \leq D_{HH}^{f}(p,q) \leq \frac{1}{2} D_f(p,q), \tag{1.16}$$

provided that f is convex and normalised, i.e., $f(1) = 0$.

In this paper we point out new inequalites for the $HH-$divergence, which also improve the above result (1.16).

For classical and new results in comparing different kinds of divergence measures, see the papers [1]-[45] where further references are given.

2. The Results

In the following, we assume everywhere that the mapping $f : (0,\infty) \to \mathbb{R}$ is convex and normalised.

The following result holds.

Theorem 1. *Let $p,q \in \not\leq$, then we have the inequality,*

$$\begin{aligned} & D_f\left(p, \frac{1}{2}p + \frac{1}{2}q\right) \\ \leq\ & \lambda D_f\left(p, p + \frac{\lambda}{2}(q-p)\right) + (1-\lambda) D_f\left(p, \frac{p+q}{2} + \frac{\lambda}{2}(q-p)\right) \\ \leq\ & D_{HH}^{f}(p,q) \leq \frac{1}{2}\left[D_f(p,(1-\lambda)p + \lambda q) + (1-\lambda) D_f(p,q)\right] \\ \leq\ & \frac{1}{2} D_f(p,q), \end{aligned} \tag{2.1}$$

for all $\lambda \in [0,1]$.

Proof. First, the following refinement of the Hermite-Hadamard inequality is proved.

$$\begin{aligned} & f\left(\frac{a+b}{2}\right) \\ \leq\ & \lambda f\left(a + \lambda \cdot \frac{b-a}{2}\right) + (1-\lambda) f\left(\frac{a+b}{2} + \lambda \cdot \frac{b-a}{2}\right) \\ \leq\ & \frac{1}{b-a}\int_a^b f(u)\,du \leq \frac{1}{2}\left[f((1-\lambda)a + \lambda b) + \lambda f(a) + (1-\lambda) f(b)\right] \\ \leq\ & \frac{f(a)+f(b)}{2} \end{aligned} \tag{2.2}$$

for all $\lambda \in [0,1]$.

Applying the Hermite-Hadamard inequality on each subinterval $[a,(1-\lambda)a+\lambda b]$, $[(1-\lambda)a+\lambda b,b]$, we have,

$$\begin{aligned}
& f\left(\frac{a+(1-\lambda)a+\lambda b}{2}\right)\times[(1-\lambda)a+\lambda b-a] \\
\leq & \int_a^{(1-\lambda)a+\lambda b} f(u)\,du \\
\leq & \frac{f((1-\lambda)a+\lambda b)+f(a)}{2}\times[(1-\lambda)a+\lambda b-a]
\end{aligned}$$

and

$$\begin{aligned}
& f\left(\frac{(1-\lambda)a+\lambda b+b}{2}\right)\times[b-(1-\lambda)a-\lambda b] \\
\leq & \int_{(1-\lambda)a+\lambda b}^{b} f(u)\,du \\
\leq & \frac{f(b)+f((1-\lambda)a+\lambda b)}{2}\times[b-(1-\lambda)a-\lambda b],
\end{aligned}$$

which are clearly equivalent to

$$\begin{aligned}
\lambda f\left(a+\lambda\cdot\frac{b-a}{2}\right) &\leq \frac{1}{b-a}\int_a^{(1-\lambda)a+\lambda b} f(u)\,du \\
&\leq \frac{\lambda f((1-\lambda)a+\lambda b)+\lambda f(a)}{2}
\end{aligned}\tag{2.3}$$

and

$$\begin{aligned}
& (1-\lambda)f\left(\frac{a+b}{2}+\lambda\cdot\frac{b-a}{2}\right) \\
\leq & \frac{1}{b-a}\int_{(1-\lambda)a+\lambda b}^{b} f(u)\,du \\
\leq & \frac{(1-\lambda)f(b)+(1-\lambda)f((1-\lambda)a+\lambda b)}{2}
\end{aligned}\tag{2.4}$$

respectively.

Summing (2.3) and (2.4), we obtain the second and first inequality in (2.2).

By the convexity property, we obtain

$$\begin{aligned}
& \lambda f\left(a+\lambda\cdot\frac{b-a}{2}\right)+(1-\lambda)f\left(\frac{a+b}{2}+\lambda\cdot\frac{b-a}{2}\right) \\
\geq & f\left[\lambda\left(a+\lambda\cdot\frac{b-a}{2}\right)+(1-\lambda)\left(\frac{a+b}{2}+\lambda\cdot\frac{b-a}{2}\right)\right] \\
= & f\left(\frac{a+b}{2}\right)
\end{aligned}$$

and the first inequality in (2.1) is proved.

The latter inequality is obvious by the convexity property of f.

Now, if we choose $a = 1$ and $b = \frac{q(x)}{p(x)}$, $x \in \chi$, in (2.2) and multiply by $p(x) \geq 0$, $x \in \chi$, we get

$$\begin{aligned}
& p(x) f\left(\frac{p(x)+q(x)}{2p(x)}\right) \\
\leq\ & \lambda p(x) f\left(\frac{p(x)+\lambda(q(x)-p(x))}{2p(x)}\right) \\
& +(1-\lambda) p(x) f\left(\frac{p(x)+q(x)}{2p(x)}+\frac{\lambda(q(x)-p(x))}{2p(x)}\right) \\
\leq\ & \frac{p^2(x)}{q(x)-p(x)} \int_1^{\frac{q(x)}{p(x)}} f(u)\, du \\
\leq\ & \frac{1}{2}\left[f\left(\frac{(1-\lambda)p(x)+\lambda q(x)}{p(x)}\right) p(x)+\lambda p(x) f(1)+(1-\lambda) p(x) f\left(\frac{q(x)}{p(x)}\right)\right] \\
\leq\ & \frac{p(x) f(1)+p(x) f\left(\frac{q(x)}{p(x)}\right)}{2}.
\end{aligned}$$

Integrating on χ and taking into account the definition of $f-$divergence (1.10) and the Hermite-Hadamard divergence (1.15), we obtain (2.1). ∎

Remark 1. *If $\lambda = 0$ or $\lambda = 1$, then by (2.1), we obtain the inequality (1.16).*

Corollary 1. *Let $p, q \in \Omega$, then we have the inequality,*

$$\begin{aligned}
D_f\left(p, \frac{p+q}{2}\right) &\leq \frac{1}{2}\left[D_f\left(p, \frac{3p+q}{4}\right)+D_f\left(p, \frac{p+3q}{4}\right)\right] \\
&\leq D_{HH}^f(p, q) \leq \frac{1}{2}\left[D_f\left(p, \frac{p+q}{2}\right)+\frac{1}{2} D_f(p, q)\right] \\
&\leq \frac{1}{2} D_f(p, q),
\end{aligned} \tag{2.5}$$

which is obtained by taking $\lambda = \frac{1}{2}$ in (2.1).

Remark 2. *If we replace λ by $(1-\lambda)$ in (2.1), we have,*

$$\begin{aligned}
& D_f\left(p, \frac{p+q}{2}\right) \\
\leq\ & (1-\lambda) D_f\left(p, \frac{p+q}{2}+\lambda(p-q)\right)+\lambda D_f\left(p, q+\lambda \frac{p-q}{2}\right) \\
\leq\ & D_{HH}^f(p, q) \leq \frac{1}{2}\left[D_f(p, \lambda p+(1-\lambda) q)+\lambda D_f(p, q)\right] \\
\leq\ & \frac{1}{2} D_f(p, q).
\end{aligned} \tag{2.6}$$

Now, if we add (2.1) and (2.6) and divide by 2, we can state the following corollary.

Corollary 2. *Let $p, q \in \Omega$, then we have the inequality,*

$$\begin{aligned}
&D_f\left(p, \frac{p+q}{2}\right) \\
\leq\ & \lambda\left[D_f\left(p, p+\frac{\lambda}{2}(q-p)\right)+D_f\left(p, q+\frac{\lambda}{2}(p-q)\right)\right] \\
&+(1-\lambda)\left[D_f\left(p, \frac{p+q}{2}+\frac{\lambda}{2}(q-p)\right)+D_f\left(p, \frac{p+q}{2}+\frac{1}{2}(p-q)\right)\right] \\
\leq\ & D_{HH}^f(p, q) \\
\leq\ & \frac{1}{4}\left[D_f(p,(1-\lambda) p+\lambda q)+D_f(p, \lambda p+(1-\lambda) q)+D_f(p, q)\right] \\
\leq\ & \frac{1}{2} D_f(p, q),
\end{aligned} \tag{2.7}$$

for all $\lambda \in [0,1]$.

We also define the divergence.

$$\begin{aligned}
H_f(p, q; t) \quad : &= \int_\chi p(x) f\left[\frac{tq(x)+(1-t) p(x)}{p(x)}\right] d\mu(x) \\
&= D_f(p, tq+(1-t) p).
\end{aligned} \tag{2.8}$$

Theorem 2. *Let $p, q \in \Omega$, then,*

(i) *$H_f(p, q; \cdot)$ is convex on $[0,1]$;*
(ii) *We have the bounds*

$$\inf_{t \in [0,1]} H_f(p, q; t)=H_f(p, q; 0)=0, \tag{2.9}$$

$$\sup_{t \in [0,1]} H_f(p, q; t)=H_f(p, q; 1)=D_f(p, q), \tag{2.10}$$

and the inequality

$$H_f(p, q; t) \leq t D_f(p, q) \quad \text{for all } t \in [0,1]. \tag{2.11}$$

(iii) *The mapping $H_f(p, q; \cdot)$ is monotonic nondecreasing on $[0,1]$.*

Proof. (i) Let t_1, $t_2 \in [0,1]$ and $\alpha, \beta \in [0,1]$ with $\alpha+\beta=1$, then,

$$\begin{aligned}
& H_f(p, q; \alpha t_1+\beta t_2) \\
=\ & \int_\chi p(x) f\left[\frac{(\alpha t_1+\beta t_2) q(x)+(1-\alpha t_1-\beta t_2) p(x)}{q(x)}\right] d\mu(x) \\
=\ & \int_\chi p(x) f\left[\alpha \cdot \frac{\left[t_1 q(x)+(1-t_1) p(x)\right]}{q(x)}+\beta \cdot \frac{\left[t_2 q(x)+(1-t_2) p(x)\right]}{q(x)}\right] d\mu(x) \\
\leq\ & \alpha \cdot \int_\chi p(x) f\left[\frac{t_1 q(x)+(1-t_1) p(x)}{q(x)}\right] d\mu(x) \\
& +\beta \cdot \int_\chi p(x) f\left[\frac{t_2 q(x)+(1-t_2) p(x)}{q(x)}\right] d\mu(x) \\
=\ & \alpha H_f(p, q, t_1)+\beta H_f(p, q, t_2)
\end{aligned}$$

and convexity is proved.

(ii) Using Jensen's inequality, we have:

$$\begin{aligned} H_f(p,q,t) &\geq f\left[\int_\chi p(x)\left[\frac{tq(x)+(1-t)p(x)}{q(x)}\right]d\mu(x)\right] \\ &= f\left[t\int_\chi q(x)\,d\mu(x)+(1-t)\int_\chi p(x)\,d\mu(x)\right] \\ &= f(1)=0=H_f(p,q,0)\,. \end{aligned}$$

Also, by convexity of f, we have,

$$\begin{aligned} H_f(p,q,t) &\leq \int_\chi p(x)\left[tf\left(\frac{q(x)}{p(x)}\right)+(1-t)f(1)\right]d\mu(x) \\ &\leq t\int_\chi p(x)f\left(\frac{q(x)}{p(x)}\right)d\mu(x)+(1-t)f(1)\int_\chi p(x)\,d\mu(x) \\ &= tD_f(p,q)\,, \end{aligned}$$

and the statement (ii) is proved.

(iii) Let $t_1,\, t_2 \in [0,1]$ with $t_2 > t_1$. As $H_f(p,q;\cdot)$ is convex, then

$$\frac{H_f(p,q,t_2)-H_f(p,q,t_1)}{t_2-t_1} \geq \frac{H_f(p,q,t_1)-H_f(p,q,0)}{t_1-0}$$

and as

$$H_f(p,q,t_1) \geq H_f(p,q,0)=0,$$

we deduce that $H_f(p,q,t_1) \leq H_f(p,q,t_2)$, which proves the monotonicity of $H_f(p,q,\cdot)$.

∎

Remark 3. *If we write (2.11) in terms of* $1-t$ *rather than* t*, we obtain*

$$H_f(p,q,1-t) \leq (1-t)\,D_f(p,q)\,, \quad t\in[0,1]\,. \tag{2.12}$$

Adding (2.11) and (2.12), we get,

$$H_f(p,q,t)+H_f(p,q,1-t) \leq D_f(p,q) \tag{2.13}$$

for all $t\in[0,1]$.

Remark 4. *For* $t\in\left[\frac{1}{2},1\right]$*, we have the inequality,*

$$D_f\left(p,\frac{1}{2}p+\frac{1}{2}q\right) \leq D_f(p,tq+(1-t)p) \leq tD_f(p,q)\,, \tag{2.14}$$

which is similar to (1.13).

We can also define the divergence,

$$F_f(p,q;t) := \int_\chi\int_\chi p(x)\,p(y)\,f\left[t\cdot\frac{q(x)}{p(x)}+(1-t)\cdot\frac{q(y)}{p(y)}\right]d\mu(x)\,d\mu(y)\,, \tag{2.15}$$

where $p,q\in\Omega$ and $t\in[0,1]$.

The properties of this mapping are embodied in the following theorem.

Theorem 3. *Let* $p,q\in\Omega$*, then,*

(i) $F_f(p,q;\cdot)$ *is symmetrical about* $\frac{1}{2}$*, that is,*

$$F_f(p,q;t)=F_f(p,q;1-t) \quad \textit{for all } t\in[0,1]\,. \tag{2.16}$$

(ii) F *is convex on* $[0,1]$*;*

(iii) *We have the bounds:*

$$\sup_{t\in[0,1]} F_f(p,q;t) = F_f(p,q;0) = F_f(p,q;1) = D_f(p,q), \tag{2.17}$$

$$\begin{aligned} \inf_{t\in[0,1]} F_f(p,q;t) &= F_f\left(p,q;\frac{1}{2}\right) \\ &= \int_\chi\int_\chi p(x)\,p(y)\,f\left[\frac{q(x)\,p(y)+p(x)\,q(y)}{2p(x)\,q(y)}\right] d\mu(x)\,d\mu(y) \\ &\geq 0; \end{aligned} \tag{2.18}$$

(iv) $F_f(p,q;\cdot)$ *is nondecreasing on* $\left[0,\frac{1}{2}\right]$ *and nonincreasing on* $\left[\frac{1}{2},1\right]$*;*
(v) *We have the inequality:*

$$F_f(p,q;t) \geq \max\{H_f(p,q;t);H_f(p,q;1-t)\} \quad \text{for all} \quad t\in[0,1]. \tag{2.19}$$

Proof. (i) Is obvious.
(ii) Follows by the convexity of f in a similar way to that in the proof of Theorem 2.
(iii) For all $x,y\in\chi$ we have:

$$f\left[t\cdot\frac{q(x)}{p(x)}+(1-t)\cdot\frac{q(y)}{p(y)}\right] \leq t\cdot f\left(\frac{q(x)}{p(x)}\right)+(1-t)\cdot f\left(\frac{q(y)}{p(y)}\right)$$

for any $t\in[0,1]$.
Multiplying by $p(x)\,p(y)\geq 0$ and integrating over χ^2, we write,

$$\begin{aligned} F_f(p,q;t) &\leq \int_\chi\int_\chi p(x)\,p(y)\left[t\cdot f\left(\frac{q(x)}{p(x)}\right)+(1-t)\cdot f\left(\frac{q(y)}{p(y)}\right)\right] d\mu(x)\,d\mu(y) \\ &= t\int_\chi p(y)\,d\mu(y)\int_\chi p(x)\,f\left(\frac{q(x)}{p(x)}\right) d\mu(x) \\ &\quad +(1-t)\int_\chi d\mu(x)\int_\chi p(y)\,f\left(\frac{q(y)}{p(y)}\right) d\mu(y) \\ &= t\cdot D_f(p,q)+(1-t)\cdot D_f(p,q) = D_f(p,q) \\ &= F_f(p,q;0) = F_f(p,q;1) \end{aligned}$$

and the bound (2.17) is proved.
Since f is convex, then for all $t\in[0,1]$ and $x,y\in\chi$, we have

$$\begin{aligned} &\frac{1}{2}\left\{f\left[t\cdot\frac{q(x)}{p(x)}+(1-t)\cdot\frac{q(y)}{p(y)}\right]+f\left[(1-t)\cdot\frac{q(x)}{p(x)}+t\cdot\frac{q(y)}{p(y)}\right]\right\} \\ \geq\ & f\left[\frac{1}{2}\left(\frac{q(x)}{p(x)}+\frac{q(y)}{p(y)}\right)\right]. \end{aligned}$$

Multiplying by $p(x)\,p(y)\geq 0$ and integrating over χ^2, we have,

$$\begin{aligned} &\frac{1}{2}\left[F_f(p,q;t)+F_f(p,q;1-t)\right] \\ \geq\ & \int_\chi\int_\chi p(x)\,p(y)\,f\left[\frac{1}{2}\left(\frac{q(x)}{p(x)}+\frac{q(y)}{p(y)}\right)\right] d\mu(x)\,d\mu(y) \end{aligned}$$

and the first part of (2.18) is proved.

Using Jensen's integral inequality, we may write:

$$
\begin{aligned}
& \int_{\chi}\int_{\chi} f\left[\frac{1}{2}\left(\frac{q(x)\,p(y)+p(x)\,q(y)}{p(x)\,q(y)}\right)\right] p(x)\,p(y)\,d\mu(x)\,d\mu(y) \\
\geq\ & f\left[\int_{\chi}\int_{\chi}\frac{1}{2}\left(\frac{q(x)\,p(y)+p(x)\,q(y)}{p(x)\,q(y)}\right) p(x)\,p(y)\,d\mu(x)\,d\mu(y)\right] \\
=\ & f\left[\frac{1}{2}\left[\int_{\chi} p(x)\,d\mu(x)\int_{\chi} p(y)\,d\mu(y)+\int_{\chi} q(x)\,d\mu(x)\int_{\chi} q(y)\,d\mu(y)\right]\right] \\
=\ & f(1)=0
\end{aligned}
$$

and the second part of (2.18) is proved.

(iv) The mapping $F_f(p,q;\cdot)$ being convex on $[0,1]$, we may write, for $1 \geq t_2 > t_1 \geq \frac{1}{2}$, that,

$$
\frac{F_f(p,q;t_2)-F_f(p,q;t_1)}{t_2-t_1} \geq \frac{F_f(p,q;t_1)-F_f\left(p,q;\frac{1}{2}\right)}{t_1-\frac{1}{2}}
$$

and as

$$
F_f(p,q;t_1) \geq F_f\left(p,q;\frac{1}{2}\right), \quad t_1 \geq \frac{1}{2},
$$

we deduce that $F_f(p,q;t_2) \geq F_f(p,q;t_1)$, i.e., the mapping $F_f(p,q;\cdot)$ is monotonically nondecreasing on $\left[0,\frac{1}{2}\right]$.

Similarly, we can prove that $F_f(p,q;\cdot)$ is monotonically nonincreasing on $\left[0,\frac{1}{2}\right]$, and the statement (iv) is proved.

(v) Using Jensen's integral inequality, we have,

$$
\begin{aligned}
& \int_{\chi} p(y)\, f\left[t\cdot\frac{q(x)}{p(x)}+(1-t)\cdot\frac{q(y)}{p(y)}\right] d\mu(y) \\
\geq\ & f\left[\int_{\chi} p(y)\left[t\cdot\frac{q(x)}{p(x)}+(1-t)\cdot\frac{q(y)}{p(y)}\right] d\mu(y)\right] \\
=\ & f\left[t\cdot\frac{q(x)}{p(x)}\int_{\chi} p(y)\,d\mu(y)+(1-t)\cdot\int_{\chi} q(y)\,d\mu(y)\right] \\
=\ & f\left[t\cdot\frac{q(x)}{p(x)}+(1-t)\right].
\end{aligned}
$$

Multiplying by $p(x) \geq 0$ and integrating over χ, we have,

$$
\begin{aligned}
F_f(p,q;t) &\geq \int_{\chi} p(x)\, f\left[t\cdot\frac{q(x)}{p(x)}+(1-t)\right] d\mu(x) \\
&= H_f(p,q;t),
\end{aligned}
$$

for all $t \in [0,1]$.

Now, as

$$
F_f(p,q;1-t) \geq H_f(p,q;1-t)
$$

and $F_f(p,q;t) = F_f(p,q;1-t)$ for all $t \in [0,1]$, the inequality (2.19) is completely proved.

■

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