Common fixed points for generalized \((\psi, \phi)\)-weak contractions in ordered cone metric spaces

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Abstract

The purpose of this paper is to establish coincidence point and common fixed point results for four maps satisfying generalized \((\psi, \phi)\)-weak contractions in partially ordered cone metric spaces. Also, some illustrative examples are presented.

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1. Introduction

One of the simplest and useful results in the fixed point theory is the Banach–Caccioppoli contraction mapping principle. In the last years, this principal has been generalized in many directions to generalized structures as cone metrics, partial metric spaces and quasi-metric spaces has received a lot of attention. Fixed point theory in \(K\)-metric and \(K\)-normed spaces was developed by Perov et al. [24], Mukhamedjiev and Stetsenko [16], Vandergraft [33]. For more details on fixed point theory in \(K\)-metric and \(K\)-normed spaces, we refer the reader to fine survey paper of Zabrejko [34]. The main idea was to use an ordered Banach space instead of the set of real numbers, as the codomain for a metric.

In 2007, Huang and Zhang [13] reintroduced such spaces under the name of cone metric spaces and reintroduced definition of convergent and Cauchy sequences in the terms of interior points of the underlying cone. They also proved some fixed point theorems in such spaces in the same work. After that, fixed point points in \(K\)-metric spaces have been the subject of intensive research (see, e.g.,
The main motivation for such research is a point raised by Agarwal [4], that the domain of existence of a solution to a system of first-order differential equations may be increased by considering generalized distances.

Recently, Wei-Shih Du [12] used the scalarization function and investigated the equivalence of vectorial versions of fixed point theorems in $K$-metric spaces and scalar versions of fixed point theorems in metric spaces. He showed that many of the fixed point theorems for mappings satisfying contractive conditions of a linear type in $K$-metric spaces can be considered as the corollaries of corresponding theorems in metric spaces. Nevertheless, the fixed point theory in $K$-metric spaces proceeds to be actual, since the method of scalarization cannot be applied for a wide class of mappings satisfying contractive conditions more general than contractive conditions of a linear type.

On the other hand, fixed point theory has developed rapidly in metric spaces endowed with a partial ordering. One of results in this direction was given by Ran and Reurings [26] who presented its applications to matrix equations. Subsequently, Nieto and Rodríguez-López [22] extended the result of Ran and Reurings for nondecreasing mappings and applied it to obtain a unique solution for a first order ordinary differential equation with periodic boundary conditions. Thereafter, many authors obtained many fixed point theorems in ordered metric spaces. For more details, see [5, 6, 8, 10, 17, 19, 20, 21, 22, 27, 29, 31] and the references cited therein.

In this paper, an attempt has been made to derive some common fixed point theorems for four maps involving generalized $(\psi,\phi)$-weak contractions in ordered cone metric spaces. The presented theorems generalize, extend and improve some recent fixed point results in $K$-metric spaces.

2. Preliminaries

In what follows, we recall some notations and definitions that will be utilized in our subsequent discussion.

Let $E$ be always a Banach space.

**Definition 2.1.** A non-empty subset $K$ of $E$ is called a cone if and only if

(i) $\overline{K} = K, K \neq 0_E$ where $\overline{K}$ is the closure of $K$,
(ii) $a, b \in \mathbb{R}, a, b \geq 0, x, y \in K \Rightarrow ax + by \in K$,
(iii) $K \cap (-K) = \{0_E\}$.

A cone $K$ defines a partial ordering $\leq_E$ in $E$ by $x \leq_E y$ if and only if $y - x \in K$. We shall write $x <_E y$ to indicate that $x \leq_E y$ but $x \neq y$, while $x \ll y$ will stand for $y - x \in \text{int}(K)$, where $\text{int}(K)$ denotes the interior of $K$.

A cone $K$ is said to be normal if there exists a constant $M \geq 1$ such that $0_E \leq_E x \leq_E y$ implies $\|x\|_E \leq M\|y\|_E$. A cone $K$ is said solid if $\text{int}(K)$ is nonempty. The least positive number $M$ satisfying this inequality is called the normal constant of cone $K$. For further details on cone theory, one can refer to [28].
Definition 2.2. Let $X$ be a nonempty set. Suppose the mapping $d : X \times X \to E$ satisfies

(i) $0_E \leq_E d(x, y)$ for all $x, y \in X$ and $d(x, y) = 0_E$ if and only if $x = y$;
(ii) $d(x, y) = d(y, x)$ for all $x, y \in X$;
(iii) $d(x, y) \leq_E d(x, z) + d(z, y)$ for all $x, y, z \in X$.

Then $d$ is called a cone metric on $X$ and $(X, d)$ is called a cone metric space.

Definition 2.3. Let $(X, d)$ be a cone metric space and $\{x_n\}$ is a sequence in $X$. We say that $\{x_n\}$ is Cauchy if for every $c \in E$ with $0_E \ll c$, there exists $N \in \mathbb{N}$ such that $d(x_n, x_m) \ll c$ for all $n > m > N$. We say that $\{x_n\}$ converges to $x \in X$ if for every $c \in E$ with $0_E \ll c$, there exists $N \in \mathbb{N}$ such that $d(x_n, x) \ll c$ for all $n > N$. In this case, we denote $x_n \to x$ as $n \to \infty$.

A cone metric space $(X, d)$ is said to be complete if every Cauchy sequence in $X$ is convergent in $X$.

Definition 2.4. Let $f : E \to E$ be a given mapping. We say that $f$ is a monotone non-decreasing mapping with respect to $\leq_E$ if for every $x, y \in E$, $x \leq_E y$ implies $fx \leq_E fy$.

Definition 2.5 ([9]). Let $\psi : K \to K$ be a given function.
(i) We say that $\psi$ is strongly monotone increasing if for $x, y \in K$, we have

$$x \leq_E y \iff \psi(x) \leq_E \psi(y).$$

(ii) $\psi$ is said to be continuous at $x_0 \in K$ if for any sequence $\{x_n\}$ in $K$, we have

$$\|x_n - x_0\|_E \to 0 \implies \|\psi(x_n) - \psi(x_0)\|_E \to 0.$$

Definition 2.6. Let $(X, d)$ be a cone metric space and $f, g : X \to X$. If $w = fx = gx$, for some $x \in X$, then $x$ is called a coincidence point of $f$ and $g$, and $w$ is called a point of coincidence of $f$ and $g$. If $w = x$, then $x$ is a common fixed point of $f$ and $g$.

The pair $\{f, g\}$ is said to be compatible if and only if $\lim_{n \to +\infty} d(fgx_n, gfx_n) = 0$, whenever $\{x_n\}$ is a sequence in $X$ such that $\lim_{n \to +\infty} fx_n = \lim_{n \to +\infty} gx_n = t$ for some $t \in X$.

Definition 2.7 ([2]). Let $f$ and $g$ be two self-maps defined on a set $X$. Then $f$ and $g$ are said to be weakly compatible if they commute at every coincidence point.

Definition 2.8. Let $X$ be a nonempty set. Then $(X, \preceq)$ is called an ordered cone metric space if and only if
(i) $(X, d)$ is a metric space,
(ii) $(X, \preceq)$ is a partial order.

Definition 2.9. Let $(X, \preceq)$ be a partial ordered set. Then $x, y \in X$ are called comparable if $x \preceq y$ or $y \preceq x$ holds.

Definition 2.10 ([2]). Let $(X, \preceq)$ be a partially ordered set. A mapping $f$ is called dominating if $x \preceq fx$ for each $x \in X$. 

Common fixed points in ordered cone metric spaces 3
Example 2.11 ([2]). Let $X = [0, 1]$ be endowed with usual ordering and $f : X \to X$ be defined by $fx = \sqrt{x}$. Since $x \leq x^{\frac{1}{2}} = fx$ for all $x \in X$. Therefore $f$ is a dominating map.

Definition 2.12 ([18]). Let $(X, \leq)$ be a partially ordered set. A mapping $f$ is called dominated if $fx \preceq x$ for each $x \in X$.

Example 2.13 ([18]). Let $X = [0, 1]$ be endowed with usual ordering and $f : X \to X$ be defined by $fx = x^n$ for all $n \geq 1$. Since $fx = x^n \leq x$ for all $x \in X$. Therefore $f$ is a dominated map.

3. Common fixed point results

First, let $\Psi$ be the set of functions $\psi : K \to K$ such that

(i) $\psi$ is continuous;
(ii) $\psi(t) = 0_E$ if and only if $t = 0_E$;
(iii) $\psi$ is strongly monotone increasing.

Also, let $\Phi$ be the set of functions $\phi : \text{int}(K) \cup \{0_E\} \to \text{int}(K) \cup \{0_E\}$ such that

(i') $\phi$ is continuous;
(ii') $\phi(t) = 0_E$ if and only if $t = 0_E$;
(iii') $\phi(t) \preceq_E t$ for all $t \in \text{int}(K)$;
(iv') either $\phi(t) \leq_E d(x, y)$ or $d(x, y) \leq_E \phi(t)$ for $t \in \text{int}(K) \cup \{0_E\}$ and $x, y \in X$.

The following Lemma will be useful later.

Lemma 3.1. [30]. Let $E$ be a Banach space, $\{a_n\}, \{b_n\}$ and $\{c_n\}$ are sequences in $E$ such that $b_n \to b \in E$, $c_n \to c \in E$ as $n \to +\infty$. Suppose also that $a_n \in \{b_n, c_n\}$ for all $n \in \mathbb{N}$. Then there exists a subsequence $\{a_{n(p)}\}$ of $\{a_n\}$ such that $a_{n(p)} \to a \in \{b, c\}$ as $p \to +\infty$.

Our first result is the following.

Theorem 3.2. Let $(X, d, \preceq)$ be an ordered complete cone metric space over a solid cone $K$. Let $T, S, I, J : X \to X$ be given mappings satisfying for every pair $(x, y) \in X \times X$ such that $x$ and $y$ are comparable,

$$
\psi(d(Sx, Ty)) \leq_E \psi(\Theta(x, y)) - \phi(\Theta(x, y)),
$$

where $\Theta(x, y) \in \{d(Ix, Jy), \frac{1}{2}[d(Ix, Sx) + d(Jy, Ty)], \frac{1}{2}[d(Ix, Ty) + d(Jy, Sx)]\}$, $\psi \in \Psi$ and $\phi \in \Phi$. Suppose that

(i) $TX \subseteq IX$ and $SX \subseteq JX$;
(ii) $I$ and $J$ are dominating maps and $S$ and $T$ are dominated maps;
(iii) If for a nondecreasing sequence $\{x_n\}$ with $y_n \preceq x_n$ for all $n$ and $y_n \to u$ implies that $u \preceq x_n$.

Also, assume either

(a) $\{S, I\}$ are compatible, $S$ or $I$ is continuous and $\{T, J\}$ are weakly compatible or
(b) \(\{T, J\}\) are compatible, \(T\) or \(J\) is continuous and \(\{S, I\}\) are weakly compatible.

Then \(S, T, I\) and \(J\) have a common fixed point.

Proof. Let \(x_0\) be an arbitrary point in \(X\). Since \(TX \subseteq IX\) and \(SX \subseteq JX\), we can define the sequences \(\{x_n\}\) and \(\{y_n\}\) in \(X\) by

\[
y_{2n-1} = Sx_{2n-2} = Jx_{2n-1}, \quad y_{2n} = Tx_{2n-1} = Ix_{2n}, \quad \forall n \in \mathbb{N}.
\]

By given assumptions \(x_{2n+1} \leq Jx_{2n+1} = Sx_{2n} \leq x_{2n}\) and \(x_{2n} \leq Ix_{2n} = Tx_{2n-1} \leq x_{2n-1}\). Thus, for all \(n \geq 0\), we have

\[
x_{n+1} \leq x_n.
\]

Putting \(x = x_{2n+1}\) and \(y = x_{2n}\), from (3.3) and the considered contraction (3.1), we have

\[
\psi(d(y_{2n+1}, y_{2n+2})) = \psi(d(Sx_{2n}, Tx_{2n+1})) \\
\quad \leq E \psi(\Theta(x_{2n}, x_{2n+1})) - \phi(\Theta(x_{2n}, x_{2n+1})) \\
\quad \leq E \psi(\Theta(x_{2n}, x_{2n+1})).
\]

The function \(\psi\) is strongly increasing, so we get that

\[
d(y_{2n+1}, y_{2n+2}) \leq E \Theta(x_{2n}, x_{2n+1}).
\]

Note that

\[
\Theta(x_{2n}, x_{2n+1}) \subseteq \{d(Ix_{2n}, Jx_{2n+1}), \frac{1}{2}[d(Ix_{2n}, Sx_{2n}) + d(Jx_{2n+1}, Tx_{2n+1})], \\
\quad \frac{1}{2}[d(Ix_{2n}, Jx_{2n+1}) + d(Sx_{2n}, Jx_{2n+1})]
\]

\[
= \{d(y_{2n}, y_{2n+1}), \frac{1}{2}[d(y_{2n}, y_{2n+1}) + d(y_{2n+1}, y_{2n+2})], \\
\quad \frac{1}{2}[d(y_{2n}, y_{2n+2}) + d(y_{2n+1}, y_{2n+1})]
\]

\[
= \{d(y_{2n}, y_{2n+1}), \frac{1}{2}[d(y_{2n}, y_{2n+1}) + d(y_{2n+1}, y_{2n+2})] + \frac{1}{2}d(y_{2n}, y_{2n+2})\}.
\]

If \(\Theta(x_{2n}, x_{2n+1}) = d(y_{2n}, y_{2n+1}), (3.5)\) becomes

\[
d(y_{2n+1}, y_{2n+2}) \leq E d(y_{2n}, y_{2n+1}).
\]

If \(\Theta(x_{2n}, x_{2n+1}) = \frac{1}{2}d(y_{2n}, y_{2n+1}) + d(y_{2n+1}, y_{2n+2})\), then (3.5) becomes

\[
d(y_{2n+1}, y_{2n+2}) \leq E \frac{1}{2}[d(y_{2n}, y_{2n+1}) + d(y_{2n+1}, y_{2n+2})],
\]

so \(d(y_{2n+1}, y_{2n+2}) \leq E d(y_{2n}, y_{2n+1})\).

If \(\Theta(x_{2n}, x_{2n+1}) = \frac{1}{2}d(y_{2n}, y_{2n+2})\), by (3.4) and a triangular inequality, we find that

\[
d(y_{2n+1}, y_{2n+2}) \leq E \frac{1}{2}[d(y_{2n}, y_{2n+1}) + d(y_{2n+1}, y_{2n+2})] + \frac{1}{2}d(y_{2n+1}, y_{2n+2}),
\]

so \(d(y_{2n+1}, y_{2n+2}) \leq E d(y_{2n}, y_{2n+1})\). In all cases, we obtained that

\[
d(y_{2n+1}, y_{2n+2}) \leq E \Theta(x_{2n}, x_{2n+1}) \leq E d(y_{2n}, y_{2n+1}).
\]
Similarly, we have
\[(3.7) \quad d(y_{2n+1}, y_{2n}) \leq E \Theta(x_{2n}, x_{2n-1}) \leq E d(y_{2n}, y_{2n-1}).\]

By (3.6) and (3.7), we get that
\[(3.8) \quad d(y_{n+1}, y_n) \leq E d(y_n, y_{n-1}) \quad \text{for all } n \geq 1.\]

It follows that the sequence \(\{d(y_n, y_{n+1})\}\) is monotone non-increasing. Since \(K\) is a regular cone and \(0_E \leq E d(y_n, y_{n+1})\) for all \(n \geq 0\), there exists \(r \geq E 0_E\) such that
\[d(y_n, y_{n+1}) \to r \quad \text{as } n \to +\infty.\]

By (3.6) and (3.7), we have
\[
\lim_{n \to +\infty} \Theta(x_{2n}, x_{2n+1}) = \lim_{n \to +\infty} \Theta(x_{2n}, x_{2n-1}) = r.
\]

Now, letting \(n \to +\infty\) in (3.4) and using the continuity property of \(\psi\) and \(\phi\), we get
\[\psi(r) \leq \psi(r) - \phi(r),\]

which yields that \(\phi(r) = 0_E\). Since \(\phi(t) = 0_E \iff t = 0_E\), then \(r = 0_E\).

Therefore,
\[(3.9) \quad \lim_{n \to +\infty} d(y_n, y_{n+1}) = 0.
\]

Now, we will show that \(\{y_n\}\) is a Cauchy sequence in the cone metric space \((X, d)\). We proceed by negation and suppose that \(\{y_n\}\) is not a Cauchy sequence. Then, there exists \(\varepsilon > 0\) for which we can find two sequences of positive integers \(\{m(i)\}\) and \(\{n(i)\}\) such that for all positive integer \(i\),
\[(3.10) \quad m(i) > n(i) > i, \quad d(y_{2m(i)}, y_{2n(i)}) \geq E \varepsilon, \quad d(y_{2m(i)}, y_{2n(i)-2}) < E \varepsilon.
\]

From (3.10) and using a triangular inequality, we get
\[
\varepsilon \leq d(y_{2m(i)}, y_{2n(i)}) \leq d(y_{2m(i)}, y_{2n(i)-2}) + d(y_{2n(i)-2}, y_{2n(i)-1}) + d(y_{2n(i)-1}, y_{2n(i)}) < \varepsilon + d(y_{2n(i)-2}, y_{2n(i)-1}) + d(y_{2n(i)-1}, y_{2n(i)}).
\]

Letting \(i \to +\infty\) in the above inequality and using (3.9), we obtain
\[(3.11) \quad \lim_{i \to +\infty} d(y_{2m(i)}, y_{2n(i)}) = \varepsilon.
\]

Again, a triangular inequality gives us
\[d(y_{2n(i)}, y_{2m(i)-1}) \leq E d(y_{2n(i)}, y_{2m(i)}) + d(y_{2m(i)}, y_{2m(i)-1}),\]

and
\[d(y_{2n(i)}, y_{2m(i)}) \leq E d(y_{2n(i)}, y_{2m(i)-1}) + d(y_{2m(i)-1}, y_{2m(i)}).
\]

Letting \(i \to +\infty\) in the above inequalities and using (3.9) and (3.11), we get that
\[(3.12) \quad \lim_{i \to +\infty} d(y_{2n(i)}, y_{2m(i)-1}) = \varepsilon.
\]
Similarly, we have
\begin{equation}
\lim_{i \to +\infty} d(y_{2n(i)+1}, y_{2m(i)-1}) = \varepsilon.
\end{equation}

On the other hand, we have
\[d(y_{2n(i)}, y_{2m(i)}) \leq E \, d(y_{2n(i)}, y_{2n(i)+1} + d(y_{2n(i)+1}, y_{2m(i)}),\]
so since \(\psi\) is monotone non-decreasing and continuous, we obtain that
\begin{equation}
\psi(\varepsilon) \leq E \lim_{i \to +\infty} \psi(d(y_{2n(i)+1}, y_{2m(i)})).
\end{equation}

Now, using (3.1) for \(x = x_{2n(i)}\) and \(y = x_{2m(i)-1}\), we have
\begin{equation}
\psi(d(y_{2n(i)+1}, y_{2m(i)}) = \psi(Sx_{2n(i)}, Tx_{2m(i)-1})
\leq \psi(\Theta(x_{2n(i)}, x_{2m(i)-1})) - \phi(\Theta(x_{2n(i)}, x_{2m(i)-1})),
\end{equation}
where
\[\Theta(x_{2n(i)}, x_{2m(i)-1}) \in \{d(Ix_{2n(i)}, Jx_{2m(i)-1}), \frac{1}{2}[d(Ix_{2n(i)}, Sx_{2n(i)}) +
\frac{1}{2}[d(Ix_{2n(i)}, Tx_{2m(i)-1})] + \frac{1}{2}[d(Ix_{2n(i)}, Tx_{2m(i)-1}) + d(Jx_{2m(i)-1}, Sx_{2n(i)})]\}
= \{d(y_{2n(i)}, y_{2m(i)-1}), \frac{1}{2}[d(y_{2n(i)}, y_{2n(i)+1}) + d(y_{2m(i)-1}, y_{2m(i)}))\},
\frac{1}{2}[d(y_{2n(i)}, y_{2m(i)}) + d(y_{2m(i)-1}, y_{2m(i)+1})].\]

By (3.9), (3.12), (3.13) and having in mind Lemma 3.1, there exists a subsequence of \(\{\Theta(x_{2n(i)}, x_{2m(i)-1})\}\) still denoted \(\Theta(x_{2n(i)}, x_{2m(i)-1})\) such that
\begin{equation}
\lim_{i \to +\infty} \Theta(x_{2n(i)}, x_{2m(i)-1}) \in \{0_E, \varepsilon\}.
\end{equation}

If \(\lim_{i \to +\infty} \Theta(x_{2n(i)}, x_{2m(i)-1}) = 0_E\), then letting \(i \to +\infty\) in (3.15) and using (3.14) and the continuities of \(\psi\) and \(\phi\), we obtain that \(\psi(\varepsilon) \leq E \psi(0_E) - \phi(0_E)\), so \(\psi(\varepsilon) = 0_E\), which is a contradiction with \(\varepsilon > 0\).

If \(\lim_{i \to +\infty} \Theta(x_{2n(i)}, x_{2m(i)-1}) = \varepsilon\), then using similar arguments, we obtain that
\(\psi(\varepsilon) \leq E \psi(\varepsilon) - \phi(\varepsilon)\), so \(\phi(\varepsilon) = 0_E\), which is a contradiction.
Thus \(\{y_{2n}\}\) is a Cauchy sequence in \(X\), so \(\{y_n\}\) is also a Cauchy sequence in \(X\).

Finally, we shall prove existence of a common fixed point of the four mappings \(I, J, S\) and \(T\).
Since \(X\) is complete, there exists a point \(z\) in \(X\), such that \(\{y_{2n}\}\) converges to \(z\). Therefore,
\begin{equation}
y_{2n+1} = Jx_{2n+1} = Sx_{2n} \to z \text{ as } n \to \infty
\end{equation}
and
\begin{equation}
y_{2n+2} = Ix_{2n+2} = Tx_{2n+1} \to z \text{ as } n \to \infty.
\end{equation}
Assume that (a) holds. Suppose that $I$ is continuous. Since the pair $\{S, I\}$ is compatible, we have

\[(3.19) \quad \lim_{n \to \infty} S I x_{2n+2} = \lim_{n \to \infty} I S x_{2n+2} = Iz.\]

Also, $I x_{2n+2} = T x_{2n+1} \leq x_{2n+1}$. Now, by (3.1)

\[(3.20) \quad \psi(d(S I x_{2n+2}, T x_{2n+1})) \leq E \psi(\Theta(I x_{2n+2}, x_{2n+1})) - \phi(\Theta(I x_{2n+2}, x_{2n+1})),\]

where

\[\Theta(I x_{2n+2}, x_{2n+1}) \in \{d(I I x_{2n+2}, J x_{2n+1}), \frac{1}{2}[d(I I x_{2n+2}, S I x_{2n+2}) + d(J x_{2n+1}, T x_{2n+1})]\}.

By (3.9), (3.17), (3.18) and (3.19), we get that

\[
\lim_{n \to \infty} d(I I x_{2n+2}, J x_{2n+1}) = \lim_{n \to \infty} \frac{1}{2}[d(I I x_{2n+2}, T x_{2n+1}) + d(S I x_{2n+2}, J x_{2n+1})] = d(I z, z),
\]

\[
\lim_{n \to \infty} \frac{1}{2}[d(I I x_{2n+2}, S I x_{2n+2}) + d(J x_{2n+1}, T x_{2n+1})] = 0 E.
\]

By Lemma 3.1, there exists a subsequence of $\{\Theta(I x_{2n+2}, x_{2n+1})\}$ still denoted $\Theta(I x_{2n+2}, x_{2n+1})$ such that from the above limits

\[(3.21) \quad \lim_{n \to +\infty} \Theta(I x_{2n+2}, x_{2n+1}) \in \{0 E, d(I z, z)\}.
\]

If $\lim_{n \to +\infty} \Theta(I x_{2n+2}, x_{2n+1}) = 0 E$, then letting $n \to +\infty$ in (3.20) and using the fact that

\[
\lim_{n \to \infty} d(S I x_{2n+2}, T x_{2n+1}) = d(I z, z),
\]

and the continuities of $\psi$ and $\phi$, we obtain

\[
\psi(d(I z, z)) \leq E \psi(0 E) - \phi(0 E),
\]

so $\psi(d(I z, z)) = 0 E$, which yields that $d(I z, z) = 0 E$, so $I z = z$.

If $\lim_{n \to +\infty} \Theta(I x_{2n+2}, x_{2n+1}) = d(I z, z)$, using the similar arguments we get that

\[
\psi(d(I z, z)) - \psi(d(I z, z)) - \phi(d(I z, z)),
\]

so similarly, $I z = z$. In each case, we obtained

\[(3.22) \quad I z = z.\]

Now, $T x_{2n+1} \leq x_{2n+1}$ and $T x_{2n+1} \to z$ as $n \to \infty$, so by assumption [(iii)] we have $z \preceq x_{2n+1}$. From (3.1),

\[(3.23) \quad \psi(d(S z, T x_{2n+1})) \leq E \psi(d(\Theta(z, x_{2n+1}))) - \phi(d(\Theta(z, x_{2n+1}))).\]
where
\[
\Theta(z, x_{2n+1}) \in \{d(Iz, Jx_{2n+1}), \frac{1}{2}[d(Iz, Sz) + d(Jx_{2n+1}, Tw_{2n+1})],
\]
\[
\frac{1}{2}[d(Iz, Tx_{2n+1}) + d(Sz, Jx_{2n+1})] = \{d(z, Jx_{2n+1}), \frac{1}{2}[d(z, Sz) + d(Jx_{2n+1}, Tx_{2n+1})],
\]
\[
\frac{1}{2}[d(z, Tx_{2n+1}) + d(Sz, Jx_{2n+1})].
\]

By Lemma 3.1, there exists a subsequence of \( \{\Theta(z, x_{2n+1})\} \) still denoted \( \Theta(Ix_{2n+2}, x_{2n+1}) \) such that from the above limits
\[
\lim_{n \to \infty} \frac{1}{2}[d(z, Sz) + d(Jx_{2n+1}, Tx_{2n+1})] = \frac{1}{2}d(Ix_{2n+2}, Tx_{2n+1})
\]
\[
+ d(SI_{x_{2n+2}}, Jx_{2n+1})],
\]
\[
\lim_{n \to \infty} d(z, Jx_{2n+1}) = 0_E.
\]

By (3.9), (3.17), (3.18) and (3.19), we get that
\[
\lim_{n \to \infty} \frac{1}{2}[d(z, Sz) + d(Jx_{2n+1}, Tx_{2n+1})] = \frac{1}{2}d(Ix_{2n+2}, Tx_{2n+1})
\]
\[
+ \frac{1}{2}[d(Iz, Sz) + d(Jx_{2n+1}, Tw_{2n+1})] = 0_E.
\]

If \( \lim_{n \to \infty} \Theta(Ix_{2n+2}, x_{2n+1}) = 0_E \), then then letting \( n \to +\infty \) in (3.24) and using the fact that
\[
\lim_{n \to \infty} d(Sz, Tx_{2n+1}) = d(Sz, z),
\]
and the continuities of \( \psi \) and \( \phi \), we obtain
\[
\psi(d(Sz, z)) \leq E \psi(0_E) - \phi(0_E),
\]
so \( \psi(d(Iz, z)) = 0_E \), which yields that \( Sz = z \).

If \( \lim_{n \to \infty} \Theta(Ix_{2n+2}, x_{2n+1}) = \frac{1}{2}d(Sz, z) \) and using the similar arguments, we get that
\[
\psi(d(Sz, z)) \leq E \psi(\frac{1}{2}d(Sz, z)) - \phi(\frac{1}{2}d(Sz, z)) \leq E \psi(\frac{1}{2}d(Sz, z)),
\]
so \( d(Sz, z) \leq E \frac{1}{2}d(Sz, z) \), which holds unless \( d(Sz, z) = 0_E \), so
\[
(3.25) \quad Sz = z.
\]

Since \( S(X) \subseteq J(X) \), there exists a point \( w \in X \) such that \( Sz = Jw \). Suppose that \( Tw \neq Jw \). Since \( w \preceq Jw = Sz \preceq z \) implies \( w \preceq z \), from (3.1), we obtain
\[
(3.26) \quad \psi(d(Jw, Tw)) = \psi(d(Sz, Tw)) \leq E \psi(\Theta(z, w)) - \phi(\Theta(z, w)),
\]
where
\[
\Theta(z, w) \in \{d(Iz, Jw), \frac{1}{2}[d(Iz, Sz) + d(Jw, Tw)], \frac{1}{2}[d(Iz, Tw) + d(Sz, Jw)]\}
\]
\[
= \{0_E, \frac{1}{2}d(Jw, Tw)\}. 
\]
If $\Theta(z,w) = 0$, we easily deduce from (3.26) that $d(Jw,Tw) = 0$. Thus, we obtained
\begin{equation}
Jw = Tw. \tag{3.27}
\end{equation}
Since $T$ and $J$ are weakly compatible, $Tz = TSz = Tw = JSz = Jz.$

Now, since $Sx_{2n} \leq x_{2n}$ and $Sx_{2n} \to z$ as $n \to \infty$, so by assumption [(iii)], $z \preceq x_{2n}$. Then, from (3.1)
\begin{equation}
\psi(d(Sx_{2n},Tz)) \leq \psi(\Theta(x_{2n},z)) - \phi(\Theta(x_{2n},z)), \tag{3.28}
\end{equation}
where
\[
\Theta(x_{2n},z) \in \{d(Ix_{2n},Jz), \frac{1}{2}[d(Ix_{2n},Sx_{2n}) + d(Jz,Tz), \frac{1}{2}[d(Ix_{2n+1},Tz) + d(Sx_{2n},Jz)]
\]
\[
= \{d(Ix_{2n},Tz), \frac{1}{2}[d(Ix_{2n},Sx_{2n}), \frac{1}{2}[d(Ix_{2n+1},Tz) + d(Sx_{2n},Tz)]\}
\]
We have
\[
\lim_{n \to \infty} d(Ix_{2n},Tz) = \lim_{n \to \infty} \frac{1}{2}[d(Ix_{2n+1},Tz) + d(Sx_{2n},Tz)] = d(z,Tz),
\]
and
\[
\lim_{n \to \infty} d(Ix_{2n},Sx_{2n}) = 0, \quad \lim_{n \to \infty} d(Sx_{2n},Tz) = d(z,Tz).
\]
By Lemma 3.1, there exists a subsequence of $\{\Theta(x_{2n},z)\}$ still denoted $\Theta(x_{2n},z)$ such that from the above limits
\begin{equation}
\lim_{n \to +\infty} \Theta(x_{2n},z) \in \{0, d(z,Tz)\}. \tag{3.29}
\end{equation}
Similarly, letting $n \to \infty$ in (3.28) and having in mind (3.29), we get that
\begin{equation}
z = Tz. \tag{3.30}
\end{equation}
Therefore $Sz = Tz = Iz = Jz = z$, so $z$ is a common fixed point of $I$, $J$, $S$ and $T$. The proof is similar when $S$ is continuous.

Similarly, the result follows when (b) holds. \hfill \square

Now, it is easy to state a corollary of Theorem 3.2 involving a contraction of integral type.

**Corollary 3.3.** Let $T,S,I$ and $J$ satisfy the conditions of Theorem 3.2, except that condition (3.1) is replaced by the following: there exists a positive Lebesgue integrable function $u$ on $\mathbb{R}_+$ such that $\int_0^\varepsilon u(t)dt > 0$ for each $\varepsilon > 0$ and that
\begin{equation}
\int_0^{\psi(d(Sz,Ty))} u(t)dt \leq \int_0^{\psi(\Theta(x,y))} u(t)dt - \int_0^{\phi(\Theta(x,y))} u(t)dt. \tag{3.31}
\end{equation}
Then, $T,S,I$ and $J$ have a common fixed point.
Corollary 3.4. Let $(X,d,\preceq)$ be an ordered complete cone metric space over a solid cone $K$. Let $T,S,I:X \to X$ be given mappings satisfying for every pair $(x,y) \in X \times X$ such that $x$ and $y$ are comparable,

$$(3.32) \quad \psi(d(Sx,Ty)) \leq E \psi(\Theta_1(x,y)) - \phi(\Theta_1(x,y)),$$

where $\Theta_1(x,y) \in \{d(Ix,Iy), \frac{1}{2}[d(Ix,Sx)+d(Iy,Ty)], \frac{1}{2}[d(Ix,Ty)+d(Iy,Sx)]\}$, $\psi \in \Psi$ and $\phi \in \Phi$. Suppose that

(i) $TX \subseteq IX$ and $SX \subseteq IX$;

(ii) $I$ is a dominating map and $S$ and $T$ are dominated maps;

(iii) If for a nondecreasing sequence $\{x_n\}$ with $y_n \preceq x_n$ for all $n$ and $y_n \to u$ implies that $u \preceq x_n$.

Also, assume either

(a) $(S,I)$ are compatible, $S$ or $I$ is continuous and $(T,I)$ are weakly compatible or

(b) $(T,I)$ are compatible, $T$ or $I$ is continuous and $(S,I)$ are weakly compatible,

then $S,T$ and $I$ have a common fixed point.

Proof. It follows by taking $I = J$ in Theorem 3.2. □

Corollary 3.5. Let $(X,d,\preceq)$ be an ordered complete cone metric space over a solid cone $K$. Let $S,I:X \to X$ be given mappings satisfying for every pair $(x,y) \in X \times X$ such that $x$ and $y$ are comparable,

$$(3.33) \quad \psi(d(Sx,Sy)) \leq E \psi(\Theta_2(x,y)) - \phi(\Theta_2(x,y)),$$

where $\Theta_2(x,y) \in \{d(Ix,Iy), \frac{1}{2}[d(Ix,Sx)+d(Iy,Sy)], \frac{1}{2}[d(Ix,Sy)+d(Iy,Sx)]\}$, $\psi \in \Psi$ and $\phi \in \Phi$. Suppose that

(i) $SX \subseteq IX$;

(ii) $I$ is a dominating map and $S$ is dominated maps;

(iii) If for a nondecreasing sequence $\{x_n\}$ with $y_n \preceq x_n$ for all $n$ and $y_n \to u$ implies that $u \preceq x_n$.

Also, assume $(S,I)$ are compatible and $S$ or $I$ is continuous, then $S$ and $I$ have a common fixed point.

Proof. It follows by taking $S = T$ in Corollary 3.4. □

Corollary 3.6. Let $(X,d,\preceq)$ be an ordered complete cone metric space over a solid cone $K$. Let $T,S:X \to X$ be given mappings satisfying for every pair $(x,y) \in X \times X$ such that $x$ and $y$ are comparable,

$$(3.34) \quad \psi(d(Sx,Ty)) \leq E \psi(\Theta_3(x,y)) - \phi(\Theta_3(x,y)),$$

where $\Theta_3(x,y) \in \{d(x,y), \frac{1}{2}[d(x,Sx)+d(y,Ty)], \frac{1}{2}[d(x,Ty)+d(y,Sx)]\}$, $\psi \in \Psi$ and $\phi \in \Phi$. Suppose that

(i) $S$ and $T$ are dominated maps;

(ii) If for a nondecreasing sequence $\{x_n\}$ with $y_n \preceq x_n$ for all $n$ and $y_n \to u$ implies that $u \preceq x_n$. 

Also, assume either $S$ or $T$ is continuous, then $S$ and $T$ have a common fixed point.

**Proof.** It follows by taking $I = \text{Id}_X$, the identity on $X$, in Corollary 3.4.

**Corollary 3.7.** Let $(X, d, \preceq)$ be an ordered complete cone metric space over a solid cone $K$. Let $T, S, I, J : X \to X$ be given mappings satisfying for every pair $(x, y) \in X \times X$ such that $x$ and $y$ are comparable,

$$d(Sx, Ty) \leq E \Theta(x, y) - \phi(\Theta(x, y)),$$

where $\Theta(x, y) \in \{d(Ix, Jy), \frac{1}{2}[d(Ix, Sx) + d(Jy, Ty)], \frac{1}{2}[d(Ix, Ty) + d(Jy, Sx)]\}$ and $\phi \in \Phi$. Suppose that

(i) $TX \subseteq IX$ and $SX \subseteq JX$;
(ii) $I$ and $J$ are dominating maps and $S$ and $T$ are dominated maps;
(iii) If for a nondecreasing sequence $\{x_n\}$ with $y_n \sim x_n$ for all $n$ and $y_n \rightarrow u$ implies that $u \sim x_n$.

Also, assume either

(a) $\{S, I\}$ are compatible, $S$ or $I$ is continuous and $\{T, J\}$ are weakly compatible or
(b) $\{T, J\}$ are compatible, $T$ or $J$ is continuous and $\{S, I\}$ are weakly compatible,

then $S, T, I$ and $J$ have a common fixed point.

**Proof.** It suffices to take $\psi(t) = t$ in Theorem 3.2.

**Remark 3.8.** Theorem 3.2 extends Theorem 2.1 of Shatanawi and Samet [32] to cone metric spaces.

Now, we state the following illustrative examples.

**Example 3.9** (The case of a non-normal cone). Let $X = [0, \frac{1}{4}]$ be equipped with the usual order. Take $E = C^1([0, 1])$ and $K = \{\varphi \in E, \varphi(t) \geq 0, t \in [0, 1]\}$. Define $d : X \times X \to E$ by $d(x, y)(t) = |x - y| \varphi$ where $\varphi \in K$ is a fixed function, for example $\varphi(t) = e^t$. Then, $(X, d)$ is a complete cone metric space with a nonnormal solid cone.

Also, define $S, T, I, J : X \to X$ by $Sx = Tx = x^2$ and $Ix = Jx = x$. For all comparable $x, y \in X$, we have

$$d(Sx, Ty)(t) = d(Sx, Sx)(t) = |x^2 - y^2| e^t = |x - y| |x + y| e^t \leq \frac{1}{2} |x - y| e^t = \frac{1}{2} d(Ix, Jy)(t),$$

that is, (3.1) holds for $\psi(t) = t$ and $\phi(t) = \frac{1}{2} t$.

On the other hand, $x \leqIx = Jx$ and $Sx = Tx \leq x$ for all $x \in X$. Also, $SX \subseteq IX = JX$ and the pairs $\{S, I\} = \{T, J\}$ are compatible. All hypotheses of Theorem 3.2 are verified and $x = 0$ is a common fixed point of $S, T, I$ and $J$.

**Example 3.10.** (The case of a normal cone). Let $X = [0, \infty]$ be equipped with the usual order. Take $E = \mathbb{R}^2$ and $K = \{(x, y), x \geq 0, y \geq 0\}$. Define
The following example (which is inspired by [18]) demonstrates the validity of Theorem 3.2.

**Example 3.11** (The case of a non-normal cone). Let $X = [0, 1]$ be equipped with the usual order. Take $E = C^1_3([0, 1])$ and $K = \{ \varphi \in E, \varphi(t) \geq 0, t \in [0, 1] \}$. Define $d : X \times X \rightarrow E$ by $d(x, y)(t) = |x - y|\varphi$ where $\varphi \in K$ is a fixed function, for example $\varphi(t) = e^t$. Then, $(X, d)$ is a complete cone metric space with a nonnormal solid cone.

Define the self maps $I, J, S$ and $T$ on $X$ by

$$S(x) = \begin{cases} 0, & \text{if } x \leq \frac{1}{3} \\ \frac{1}{3}(x - \frac{1}{3}), & \text{if } x \in (\frac{1}{3}, 1] \\ 0, & \text{if } x = 0 \end{cases}, \quad T(x) = \begin{cases} 0, & \text{if } x \leq \frac{1}{3} \\ \frac{1}{3}, & \text{if } x \in (\frac{1}{3}, 1] \\ 0, & \text{if } x = 0 \end{cases},$$

$$J(x) = \begin{cases} x, & \text{if } x \in (0, \frac{1}{3}] \\ 1, & \text{if } x \in [\frac{1}{3}, 1] \end{cases}, \quad I(x) = \begin{cases} \frac{1}{3}, & \text{if } x \in (0, \frac{1}{3}] \\ 1, & \text{if } x \in [\frac{1}{3}, 1] \end{cases}.$$

Then $I$ and $J$ are dominating maps and $S$ and $T$ are dominated maps with $S(X) \subseteq J(X)$ and $T(X) \subseteq I(X)$, i.e.

<table>
<thead>
<tr>
<th>$S$ is dominated map</th>
<th>$T$ is dominated map</th>
<th>$I$ is dominating map</th>
<th>$J$ is dominating map</th>
</tr>
</thead>
<tbody>
<tr>
<td>for each $x$ in $X$</td>
<td>$Sx \leq x$</td>
<td>$Tx \leq x$</td>
<td>$x \leq Ix$</td>
</tr>
<tr>
<td>$x = 0$</td>
<td>$S(0) = 0$</td>
<td>$T(0) = 0$</td>
<td>$x \leq Jx$</td>
</tr>
<tr>
<td>$x \in (0, \frac{1}{3}]$</td>
<td>$Sx = 0 &lt; x$</td>
<td>$Tx = 0 &lt; x$</td>
<td>$x \leq \frac{1}{3} = I(x)$</td>
</tr>
<tr>
<td>$x \in (\frac{1}{3}, 1]$</td>
<td>$Sx = \frac{1}{3}(x - \frac{1}{3}) &lt; x$</td>
<td>$Tx = \frac{1}{3} &lt; x$</td>
<td>$x \leq 1 = I(x)$</td>
</tr>
</tbody>
</table>

Also, $\{S, I\}$ are compatible, $S$ is continuous and $\{T, J\}$ are weakly compatible.

Define $\psi : K \rightarrow K$ and $\phi : \text{int}(K) \cup \{0_E\} \rightarrow \text{int}(K) \cup \{0_E\}$ by

$$\psi(t) = t \quad \text{and} \quad \phi(t) = \frac{1}{2} t.$$ 

The inequality (3.1) holds for all comparable $x, y \in X$. Without loss of generality, take $x \leq y$. We consider the following cases:

(i) If $x = y = 0$, then $d(S0, T0)(t) = 0$ and (3.1) is satisfied.

(ii) For $x = 0$ and $y \in \left(0, \frac{1}{3}\right]$, then again $d(Sx, Ty)(t) = 0$ and (3.1) is satisfied.
(iii) For \( x = 0 \) and \( y \in (\frac{1}{3}, 1] \),
\[
d(Sx, Ty)(t) = \frac{1}{3} e^t < \frac{1}{2} e^t = \frac{1}{2} d(Ix, Jy)(t).
\]
(iv) For \( x, y \in (0, \frac{1}{3}] \), then \( d(Sx, Ty) = 0 \) and hence (3.1) is satisfied.
(v) For \( x = (0, \frac{1}{3}] \) and \( y \in (\frac{1}{3}, 1] \),
\[
d(Sx, Ty)(t) = \frac{1}{3} e^t < \frac{1}{2} e^t = \frac{1}{2} d(Ix, Jy)(t).
\]
(vi) For \( x, y \in (\frac{1}{3}, 1] \),
\[
d(Sx, Ty)(t) = \frac{1}{2} (1 - x) e^t \leq \frac{1}{3} e^t \leq \frac{1}{2} d(Jy, Ty)(t).
\]
All hypotheses of Theorem 3.2 are verified and \( x = 0 \) is a common fixed point of \( S, T, I \) and \( J \).

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Common fixed points in ordered cone metric spaces

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