Spatiotemporal Characteristics of Pan Evaporation and Its Influencing Factors in the Loess Plateau Region from 1960 to 2018: Postprint

Authors: Zhang Yaozong

Date: 2022-01-26T17:42:14+00:00

Abstract

Evaporation constitutes a critical process in the hydrological cycle, and investigating pan evaporation in the Loess Plateau region is of paramount significance for regional water resource utilization and protection. By compiling data on pan evaporation, air temperature, wind speed, precipitation, relative humidity, water vapor pressure, and other variables from 61 meteorological stations across the Loess Plateau, this study employs the Mann-Kendall test, cumulative anomaly analysis, and linear trend method to examine the spatiotemporal variation characteristics of pan evaporation in the Loess Plateau from 1960 to 2018, and utilizes multiple regression analysis to identify the primary meteorological factors influencing pan evaporation. The research findings demonstrate that: (1) Over the past 59 years, pan evaporation in the Loess Plateau exhibited a decreasing trend at a rate of -6 mm·(10a)-1, yet showed an increasing trend after 2000; the region' s pan evaporation underwent two transitions and three distinct stages—an increasing trend during 1960–1974, a decreasing trend during 1975–1996, and an increasing trend during 1997–2018; spring, summer, and autumn displayed decreasing trends, while winter exhibited an increasing trend. (2) Spatially, the overall and local changes in pan evaporation were asynchronous; the eastern and central Loess Plateau of Gansu, Hetao region, and Ordos Plateau showed increasing trends, whereas the Guanzhong Plain and Shanxi Loess Plateau exhibited decreasing trends. (3) Mean wind speed, sunshine duration, and water vapor pressure are, in order, the principal meteorological factors affecting pan evaporation in the Loess Plateau; the decrease in mean wind speed, reduction in sunshine duration, and increase in water vapor pressure are responsible for the decline in pan evaporation; among the seasons, wind speed is the dominant factor in spring and autumn, relative humidity in summer, and temperature in winter.

Full Text

Spatio temporal patterns of pan evaporation from 1960 to 2018 over the Loess Plateau: Changing properties and possible causes

ZHANG Yaozong[1,2], ZHANG Bo[3], ZHANG Duoyong[4], LIU Yanyan[1,2]

[1]College of Geography and History, Longdong University, Qingyang 745000, Gansu, China
[2]Qingyang Centre for the Management and Combat of Desertification, Qingyang 745000, Gansu, China
[3]College of Geography and Environmental Science, Northwest Normal University, Lanzhou 730070, Gansu, China
[4]Research Center for Historical Geography of Ordos Basin, North Minzu University, Yinchuan 750021, Ningxia, China

Abstract

Evaporation is a critical process in the hydrological cycle, and studying pan evaporation in the Loess Plateau region holds significant importance for regional water resource utilization and protection. By collecting data on pan evaporation, air temperature, wind speed, precipitation, relative humidity, and water vapor pressure from meteorological stations across the Loess Plateau, this study analyzes the spatiotemporal variation characteristics of pan evaporation from 1960 to 2018 using Kendall cumulative anomaly and linear trend methods, and explores the primary meteorological factors influencing pan evaporation through multiple regression analysis. The results indicate that: (1) Pan evaporation in the Loess Plateau showed a decreasing trend at a rate of -6 mm·$(10a)^{-1}$ from 1960 to 2018, but exhibited an increasing trend after 2000. The region experienced three distinct phases of change: an increasing trend from 1960-1974, a decreasing trend from 1975-1996, and an increasing trend from 1997-2018. (2) Spatially, the overall and local changes in pan evaporation were not synchronized. The Longdong and Longzhong Loess Plateau, Hetao region, and Ordos Plateau showed increasing trends, while the Guanzhong Plain and Shanxi Loess Plateau exhibited decreasing trends. (3) Seasonally, pan evaporation decreased in spring, summer, and autumn, but increased in winter. (4) Mean wind speed, sunshine duration, and water vapor pressure were the primary meteorological factors affecting pan evaporation in the Loess Plateau, in that order. The decrease in mean wind speed and sunshine duration, along with the increase in water vapor pressure, contributed to the reduction in pan evaporation. Among the seasons, wind speed was the dominant factor in spring and autumn, relative humidity in summer, and temperature in winter.

Keywords: pan evaporation; spatiotemporal variation; evaporation paradox; meteorological factors; Loess Plateau

1 Introduction

Water resources are the lifeline of human survival and development, and their status and variation characteristics significantly constrain sustainable socioeconomic development. Evaporation represents a crucial process in the hydrological cycle, intimately connected with energy balance and water balance. Consequently, research on evapotranspiration variation is essential for understanding climate change dynamics and clarifying regional water cycle characteristics. Due to the difficulty of observing actual evaporation, pan evaporation serves as a valuable proxy because of its high correlation with water surface evaporation. As a routine meteorological observation item with long, comparable data series, pan evaporation constitutes an important meteorological indicator for hydrological and water resource research, hydraulic engineering design, and climate zoning.

Numerous studies have demonstrated that global pan evaporation has shown a decreasing trend since the 1950s, with wind speed, solar radiation, air temperature, and relative humidity exerting significant influences. In China, most regions have exhibited decreasing annual pan evaporation in recent decades. For instance, research based on data from over 600 meteorological stations revealed a significant decreasing trend in China' s pan evaporation from 1956-2005, with more pronounced reductions in eastern, southern, and northwestern regions. Sunshine duration, mean wind speed, and diurnal temperature range were found to significantly influence water surface evaporation. Similarly, studies of the Yellow River Basin showed decreasing pan evaporation over the past 40 years, with wind speed reduction identified as the primary cause.

The Loess Plateau represents a critical ecological governance zone in China and a key region for high-quality development of the Yellow River Basin and national ecological security. Water resources constitute the main factor restricting vegetation restoration in this area, directly affecting agricultural production, ecological construction, and sustainable socioeconomic development. As a key link in the water cycle, evaporation is an important parameter influencing regional water-heat balance. However, pan evaporation data from meteorological stations often suffer from significant missing measurements, impacting the comprehensiveness and accuracy of research. This study systematically excavates and organizes pan evaporation data from meteorological stations in the region from 1960-2018, along with other relevant meteorological observation data, to analyze variation characteristics and influencing factors across six sub-regions.

1.1 Study Area

The Loess Plateau region in this study is bounded by the Yinshan Mountains to the north, Qinling Mountains to the south, Taihang Mountains to the east, and Riyue Mountain in Qinghai to the west, covering an area of 6.4×10^{5} km^{2}. This definition is consistent with the investigation scope of the Chinese Academy of Sciences Loess Plateau Comprehensive Scientific Expedition. Based on the geomorphological and physical geographical characteristics of the Loess

Plateau, the region is divided into six sub-regions for study: Longzhong Loess Plateau (I), Longdong Loess Plateau (II), Guanzhong Plain (III), Shanxi Loess Plateau (IV), Hetao region (V), and Ordos Plateau (VI).

1.2 Data Sources

This study utilizes pan evaporation (Epan) data from meteorological stations across the Loess Plateau, measured using a 20 cm evaporation pan, along with meteorological data including mean temperature (T), minimum temperature (Tmin), maximum temperature (Tmax), precipitation (Pre), mean wind speed (u_2), sunshine duration (Sd), water vapor pressure (es), and relative humidity (Rh). The meteorological data were obtained from the China Meteorological Data Sharing Service Network (http://data.cma.cn/). Due to substantial missing data in pan evaporation records, stations with continuous time series of less than 10 years were excluded. Through metadata analysis and strict quality control, 61 stations with complete pan evaporation and related meteorological data from 1960-2018 were selected for analyzing regional variation characteristics and influencing factors.

1.3 Methods

1.3.1 Linear Trend and Kendall Methods

This study employs linear trend analysis and Kendall non-parametric statistical test (Kendall test) to analyze trends in Epan over the Loess Plateau, and uses cumulative anomaly and Mann-Kendall abrupt change test to identify break points. Linear trend analysis offers simplicity and clear physical meaning, enabling quantitative assessment of trend values and significance testing through correlation coefficients. The Kendall test is recommended by the World Meteorological Organization for environmental data time series trend analysis and is an effective tool for detecting monotonic trends and abrupt changes. These methods have been widely applied in climate change research.

1.3.2 Multiple Linear Regression Analysis

In multi-element geographical systems, various factors interact and correlate with each other, making multiple geographical regression models more universally applicable. Since multiple factors influence Epan, standardized data were used in multiple regression analysis to identify primary meteorological elements affecting Epan. F-test was applied to determine the variance contribution of each factor to pan evaporation, thereby identifying dominant meteorological factors for Epan variation in each region.

The multiple linear regression model structure is expressed as: $y = b_0 + b_1x_1 + \cdots + b x$, where y is the dependent variable, $x_1 \cdots x$ are independent variables, b_0 is the constant term, and $b_1 \cdots b$ are partial regression coefficients. The partial regression coefficient b represents the average change in y when independent variable x changes by one unit while other independent variables x remain fixed. Regression coefficients were obtained using the least squares method, and the established model was subjected to significance testing using F-test.

2 Results and Analysis

2.1.1 Interannual Variation Characteristics of Pan Evaporation

Linear trend analysis reveals that pan evaporation in the Loess Plateau showed an overall decreasing trend from 1960-2018, with a climate tendency rate of -6 mm · $(10a)^{-1}$, which passed the significance test. This trend is consistent with pan evaporation changes across China and the Yellow River Basin, all showing decreasing trends. Specifically, from 1960-1996, the Loess Plateau exhibited a significant decreasing trend with a climate tendency rate of -59 mm · $(10a)^{-1}$, exceeding the reduction rate in most other regions of China during the same period. After 1997, pan evaporation showed an increasing trend with a climate tendency rate of 26 mm · $(10a)^{-1}$.

Seasonally, the climate tendency rates for spring, summer, autumn, and winter were -14 mm · $(10a)^{-1}$, -16 mm · $(10a)^{-1}$, -1 mm · $(10a)^{-1}$ (not significant), and 16 mm · $(10a)^{-1}$, respectively. Spring and summer contributed most to the annual reduction, while winter' s increasing trend was the main reason for the slowed reduction rate in recent years.

Spatially, pan evaporation changes showed poor consistency, with local and overall changes being asynchronous. Both decreasing and increasing stations coexisted: 57% of stations showed decreasing trends (with 28% passing significance tests), while 43% showed increasing trends (with 13% passing significance tests). Increasing trends were mainly distributed in the Longdong and Longzhong Loess Plateau, Hetao region, and Ordos Plateau, while decreasing trends occurred primarily in the Guanzhong Plain and Shanxi Loess Plateau. This spatial heterogeneity is consistent with phenomena observed across China and the Yellow River Basin.

Among the six sub-regions, Longdong Loess Plateau, Hetao region, and Ordos Plateau showed increasing trends with climate tendency rates of 3 mm · $(10a)^{-1}$, 18 mm · $(10a)^{-1}$, and 17 mm · $(10a)^{-1}$, respectively. Longzhong Loess Plateau, Guanzhong Plain, and Shanxi Loess Plateau showed decreasing trends with rates of -8 mm · $(10a)^{-1}$, -22 mm · $(10a)^{-1}$, and -13 mm · $(10a)^{-1}$, respectively. The decreasing rate exceeded the increasing rate across all regions.

2.1.2 Abrupt Change Analysis of Pan Evaporation

Mann-Kendall test analysis shows that the UF and UB curves for Loess Plateau Epan intersect in 1975 and 1996, indicating these as the main turning years. The cumulative anomaly curve reveals three distinct phases: an increasing trend from 1960-1974, a decreasing trend from 1975-1996, and an increasing trend from 1997-2018. Sub-regions show similar patterns, though with some variations in turning points and trend magnitudes.

2.2 Analysis of Meteorological Factors Influencing Pan Evaporation

Multiple regression analysis with F-test identification of variance contributions reveals that mean wind speed, sunshine duration, and water vapor pressure are the primary meteorological factors affecting Epan across the Loess Plateau, in that order. Wind speed and sunshine duration have positive effects, while water vapor pressure has a negative effect. However, the dominant factor varies by sub-region: wind speed dominates in most regions, sunshine duration is primary in some areas, and temperature is the leading factor in others, reflecting significant geographical differences.

Seasonal analysis shows distinct patterns: in spring, mean minimum temperature and wind speed are most significant; in summer, relative humidity is the dominant factor, with water vapor pressure and precipitation also important; in autumn, wind speed is primary across most regions; in winter, minimum temperature, sunshine duration, and relative humidity are the main influencing factors.

From 1960-2018, mean wind speed and sunshine duration in the Loess Plateau decreased at rates of -0.06 $m \cdot s^{-1} \cdot (10a)^{-1}$ and -42 $h \cdot (10a)^{-1}$, respectively, while water vapor pressure increased at 0.04 $hPa \cdot (10a)^{-1}$. The combined effect of these three factors resulted in the overall decreasing trend of Epan. The phase changes in these factors correspond to the three distinct periods of Epan variation, demonstrating that pan evaporation changes result from the comprehensive, nonlinear interaction of multiple meteorological elements.

3 Discussion

Pan evaporation variation results from the combined effects of multiple meteorological factors through complex nonlinear interactions, and cannot be explained by a single environmental factor. From 1960-2018, the dynamic, thermal, and moisture factors affecting pan evaporation in the Loess Plateau all underwent changes with distinct phased characteristics, leading to different variation features of pan evaporation.

Previous studies have identified wind speed, sunshine duration, diurnal temperature range, and relative humidity as key factors affecting national-scale Epan trends. While wind speed is confirmed as the primary factor for the Loess Plateau, significant regional and seasonal differences exist. Some studies have reported that surface wind speed in China began increasing after 2014, but regional variations remain pronounced. In the Loess Plateau, wind speed continues to show decreasing trends in some areas, while Epan increases after 1997 despite wind speed changes, indicating that sunshine duration and water vapor pressure also exert important controls.

As a climatic transition zone, the Loess Plateau exhibits complex change mechanisms. Future research should consider additional factors beyond those examined in this study, including solar radiation, cloud cover, and underlying surface properties, to more comprehensively understand pan evaporation variation mechanisms.

4 Conclusions

(1) From 1960-2018, pan evaporation in the Loess Plateau showed a decreasing trend at a rate of -6 $mm \cdot (10a)^{-1}$, consistent with trends across China and the Yellow River Basin but with a larger magnitude. Two turning points (1975 and 1996) divided the period into three phases: 1960-1974 showed a weak increasing trend, 1975-1996 a decreasing trend, and 1997-2018 an increasing trend.

(2) Spatially, 57% of stations showed decreasing trends, while 43% showed increasing trends, with poor synchronization between overall and local changes. The Longdong and Longzhong Loess Plateau, Hetao region, and Ordos Plateau exhibited increasing trends, while the Guanzhong Plain and Shanxi Loess Plateau showed decreasing trends.

(3) Mean wind speed, sunshine duration, and water vapor pressure were the primary meteorological factors influencing pan evaporation, in that order. The decrease in mean wind speed (-0.05 $m \cdot s^{-1} \cdot (10a)^{-1}$) and sunshine duration (-41 $h \cdot (10a)^{-1}$), combined with the increase in water vapor pressure (0.04 $hPa \cdot (10a)^{-1}$), were the main reasons for the decreasing trend of pan evaporation. Dynamic factors dominated in spring and autumn, moisture factors in summer, and thermal factors in winter.

References

[1] Qiu Xinfa, Liu Changming, Zeng Yan. Changes of pan evaporation in the recent 40 years over the Yellow River Basin[J]. Journal of Natural Resource, 2003, 18(4): 437-442.

[2] Roderick M L, Hobbins M T, Farquhar G D. Pan evaporation trends and the terrestrial water balance. I. energy balance and interpretation[J]. Geography Compass, 2009, 3(2): 746-760.

[3] Roderick M L, Hobbins M T, Farquhar G D. Pan evaporation trends and the terrestrial water balance. II. energy balance and interpretation[J]. Geography Compass, 2009, 3(2): 761-780.

[4] Write Committee of the Third National Assessment Report of Climate Change. The Third National Assessment Report of Climate Change[M]. Beijing: Science Press, 2015.

[5] Su T, Feng T C, Feng G L. Evaporation variability under climate warming in five reanalyses and its association with pan evaporation over China[J]. Journal

of Geophysical Research: Atmospheres, 2015, 120: 8080-8098.

[6] Zuo Hongchao, Bao Yan, Zhang Cunjie, et al. An analytic and numerical study on the physical meaning of pan evaporation and its trend in recent 40 years[J]. Chinese Journal of Geophysics, 2006, 49(3): 680-688.

[7] Ren Guoyu, Guo Jun. Changes of pan evaporation in the recent 40 years over the Yellow River Basin[J]. Journal of Natural Resource, 2006, 21(1): 32-42.

[8] Shen Shuanghe, Sheng Qiong. Changes in pan evaporation and its cause in China in the last 45 years[J]. Acta Meteorologica Sinica, 2008, 66(3): 452-460.

[9] Qi Tianyao, Zhang Qiang, Wang Yue, et al. Spatiotemporal patterns of pan evaporation in 1960-2005 in China: Changing properties and possible causes[J]. Acta Geographica Sinica, 2015, 35(12): 1599-1606.

[10] Cong Zhentao, Ni Guangheng, Yang Dangwen, et al. Does evaporation paradox exist in China?[J]. Advance in Water Science, 2008, 19(2): 147-152.

[11] Brutsaert W, Parlange M B. Hydrologic cycle explains the evaporation paradox[J]. Nature, 1998, 396(6706): 30.

[12] Yang Siqi, Zhang Qiang, Xi Xiaoxia, et al. Comparative analysis of pan evaporation trends between the summer monsoon transition region and other regions of China[J]. Plateau Meteorology, 2018, 37(4): 1017-1024.

[13] Zhang Q, Wang W Y, Wang S, et al. Increasing trend of pan evaporation over the semiarid Loess Plateau under a warming climate[J]. Journal of Applied Meteorology and Climatology, 2016, 55(9): 1961-1970.

[14] Chen J L, Yang H, Lyu M Q, et al. Estimation of monthly pan evaporation using support vector machine in Three Gorges Reservoir Area, China[J]. Theoretical & Applied Climatology, 2019, 138(4): 2529-2542.

[15] Gao Y, Zhao C, Ashiq M W, et al. Actual evapotranspiration of subalpine meadows in the Qilian Mountains, Northwest China[J]. Journal of Arid Land, 2019, 11(3): 371-384.

[16] Liu Chun, Wang Shourong, Liang Youye, et al. Analysis of pan evaporation change and the influence factors in the Yellow River Basin in 1961-2010[J]. Climate Change Research, 2013, 9(5): 327-334.

[17] Yang Siqi, Zhang Qiang, Xi Xiaoxia, et al. The reason of trends in pan evaporation in the summer monsoon transition region contrary to those of other regions in China[J]. Chinese Journal of Atmospheric Sciences, 2019, 43(6): 1441-1450.

[18] Comprehensive Scientific Investigation Team of Chinese Academy of Sciences on Loess Plateau. Natural Environment and its Evolution in Loess Plateau[M]. Beijing: Science Press, 1991.

[19] Zhang Yaozong. Study on Climate Change in the Loess Plateau of China and Its Response to Global Climate Change[D]. Lanzhou: Northwest Normal

University, 2016.

[20] Wei Fengying. Climatological Statistical Diagnosis and Prediction Technology[M]. Beijing: Meteorological Press, 2007.

[21] Xu Jianhua. Quantitative Geography[M]. 2nd Ed. Beijing: Higher Education Press, 2014: 208-101.

[22] Zheng Qianqian, Dai Pengchao, Zhang Jinyan, et al. Evapotranspiration in the Jinghe River Basin based on the surface energy balance system[J]. Arid Zone Research, 2020, 37(6): 1378-1387.

[23] Shen Luting, Zhang Fangmin, Huang Jin, et al. Climate characteristics of day and night precipitation during the growing season in Inner Mongolia from 1961 to 2018[J]. Arid Zone Research, 2020, 37(6): 1519-1527.

[24] Ma Aihua, Yue Dapeng, Zhao Jingbo, et al. Spatiotemporal variation and effect of extreme precipitation in Inner Mongolia in recent 60 years[J]. Arid Zone Research, 2020, 37(1): 74-85.

[25] Jiao Wenhui, Zhang Bo, Huang Tao, et al. Spatiotemporal change of extreme temperature in the Hedong Region in recent 30 years[J]. Arid Zone Research, 2019, 36(6): 1466-1477.

[26] Yang Siqi. Spatiotemporal Variation of Climatic Trend Rate of Pan Evaporation and its Relationship with Climatic Factors in China[D]. Lanzhou: Lanzhou University, 2019.

[27] Liu Min, Shen Yanjun, Zeng Yan, et al. Changing trend of pan evaporation and its cause over the past 50 years in China[J]. Acta Geographica Sinica, 2009, 64(3): 259-269.

[28] Liu B, Xu M, Henderson M, et al. A spatial analysis of pan evaporation trends in China, 1955-2000[J]. Journal of Geophysical Research: Atmospheres, 2004, 109(15): 566-589.

[29] Ma Haijiao, Cui Chengfeng, Li Hongbin, et al. Analysis on variation characteristics of pan evaporation in recent 34 years in the Loess Plateau[J]. Journal of Anhui Agricultural Sciences, 2013, 41(10): 4506-4509.

[30] Guo Jun, Ren Guoyu. Recent change of pan evaporation and possible climate factors over the Huang Hai watershed, China[J]. Advance in Water Science, 2005, 16(5): 666-672.

[31] Liu X M, Zheng H X, Zhang M H, et al. Identification of dominant climate factor for pan evaporation trend in the Tibetan Plateau[J]. Journal of Geographical Sciences, 2016, 21(4): 594-608.

[32] Zheng H X, Liu X M, Liu C M. Assessing contributions to pan evaporation trends in Haihe River Basin[J]. Journal of Geophysical Research, 2009, 114: 1-12.

[33] Liu Binhui. The Change Character of Climate and Its Influence on Forest Related Climate Variables[D]. Haerbin: Northeast Foresty University, 2011.

[34] Fan Lingli, Guo Pinwen, Zhang Fuying, et al. Changes in pan evaporation and its cause over Guangdong[J]. Acta Geographica Sinica, 2010, 33(6): 703-710.

[35] He Enpei. Spatial Distribution and Temporal Trend of Pan Evaporation in TGRA in Recent 60 Years[D]. Beijing: University of Chinese Academy of Sciences, 2017.

[36] Ma Xuening, Zhang Mingjun, Wang Shengjie, et al. Evaporation paradox in the Yellow River Basin[J]. Acta Geographica Sinica, 2012, 67(5): 645-656.

[37] Chen Bolong, Zuo Hongchao, Gao Xiaoqing, et al. Study on pan evaporation and energy change process by micro meteorological method[J]. Plateau Meteorology, 2017, 36(1): 87-97.

[38] Zuo H C, Li D L, Hu Y Q, et al. Characteristics of climatic trends and correlation between pan evaporation and environmental factors in the last 40 years over China[J]. Chinese Science Bulletin, 2005, 50(12): 1235-1241.

[39] Yang Q, Li M, Zu Z, et al. Has the stilling of the surface wind speed ended in China?[J]. Science China Earth Sciences, 2021, 64(7): 1036-1049.

Figures

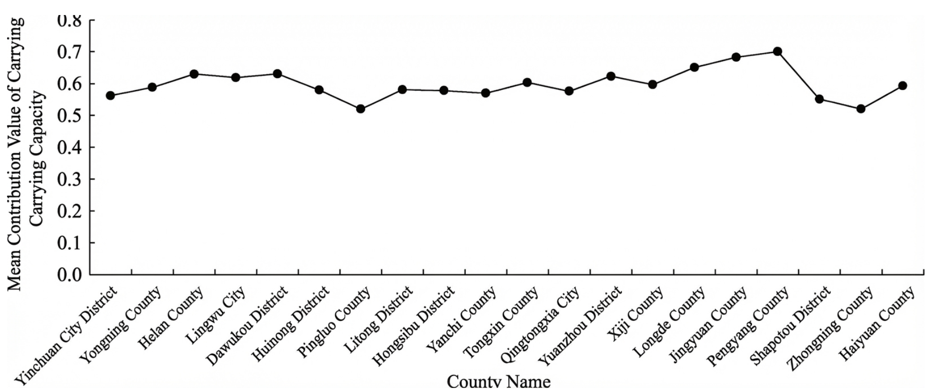

Figure 1: Figure 1

Source: ChinaXiv —Machine translation. Verify with original.

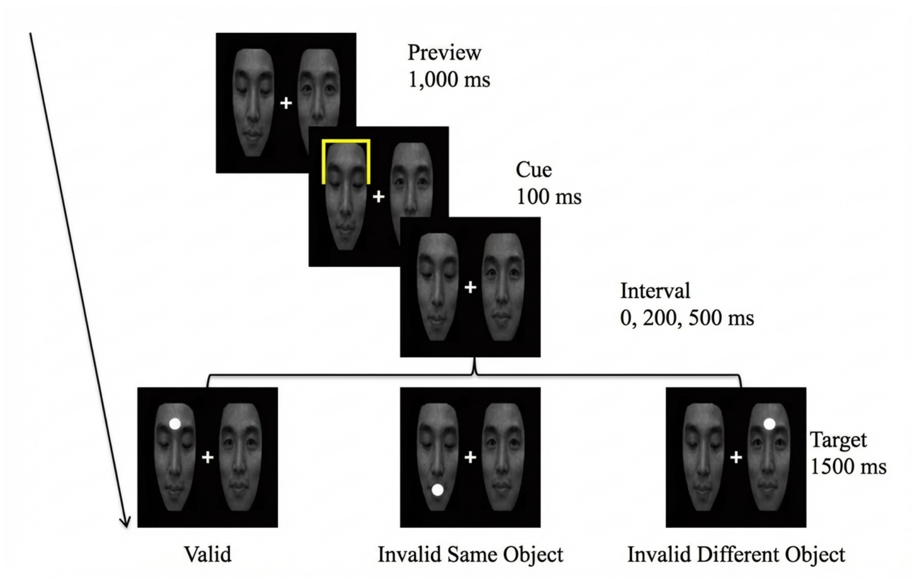

Figure 2: Figure 2

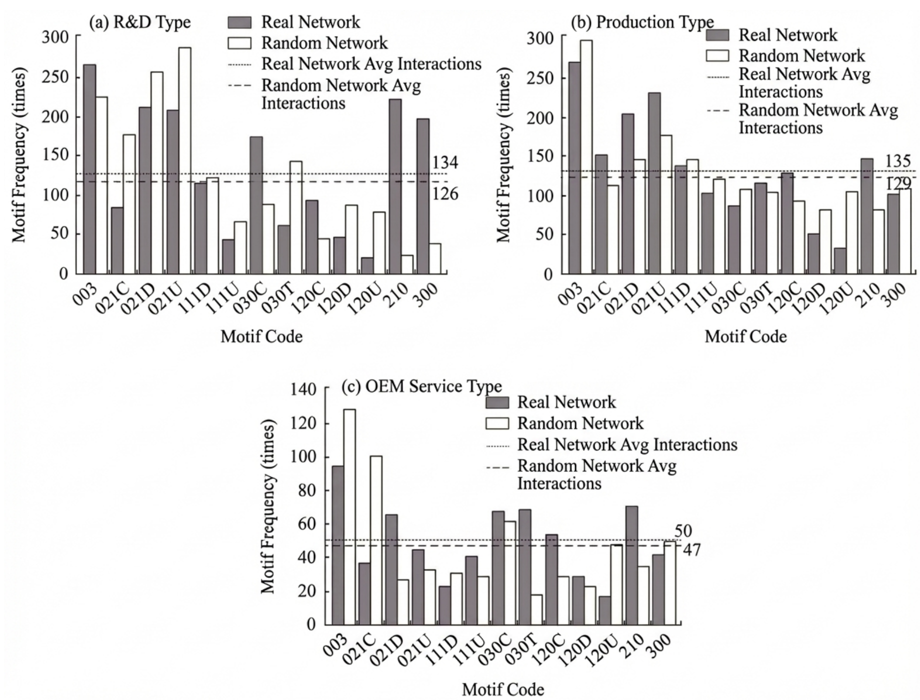

Figure 3: Figure 3

Figure 4: Figure 4

Figure 5: Figure 5